APPENDIX F

HAZARDS ANALYSIS OF A PROPOSED LNG IMPORT TERMINAL IN THE PORT OF LONG BEACH, CALIFORNIA

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IN THE PORT OF LONG BEACH, CALIFORNIA

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HAZARDS ANALYSIS
OF A PROPOSED LNG IMPORT TERMINAL
IN THE PORT OF LONG BEACH, CALIFORNIA

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SECTION 1
INTRODUCTION

The possibility of large spills of liquefied natural gas (LNG) from large insulated storage tanks or ocean-going LNG tank ships has received increased attention as the demand for natural gas in the United States requires increased importation from foreign sources. This attention has resulted because:

- LNG is a relatively new commodity in many parts of the U.S.,
- LNG has hazardous properties,
- LNG is stored at very low temperatures in large insulated storage tanks, and
- LNG is transported in large, highly visible ships.

LNG spills are considered serious events because the spill surface provides a large heat source that will rapidly vaporize the LNG. The resultant flammable vapor cloud can travel downwind before diluting to safe concentrations. If the flammable vapor is ignited, a vapor cloud fire followed by a pool fire can occur.

1.1 LNG Import Terminal Overview

Sound Energy Solutions (SES) proposes to build an LNG import terminal in the Port of Long Beach in Long Beach, California. The proposed terminal is to be located on Pier T East. The terminal will receive LNG via LNG tank ships on a regular basis. Once the LNG is unloaded from the LNG tank ships into two insulated storage tanks, it will be vaporized for introduction to the local gas transmission pipeline grid or exported by tank truck to regional locations where the LNG is used for vehicular fuel.

Depending on the overseas source of the LNG, a portion of LNG may have to be processed to reduce the amount of the heavier hydrocarbon components of the fluid (e.g., propane and butane) so that the vaporized LNG (natural gas) and product LNG (vehicular fuel) will meet fuel specifications.

The LNG tank ship used in the release and consequence modeling conducted in this work is a 125,000 m^3 membrane tank ship. A membrane tank ship was chosen based on a review of the spherical (Moss) tank ship design data that indicates that the spherical design may be more effective in responding to certain types of LNG ship accidents without loss of product [Glasfeld, 1979]. The choice of the membrane design instead of the spherical design as the basis of one of the project's components will not significantly affect the calculations made for, or conclusions drawn from, this study.

The primary components of the proposed terminal are shown on the plot plan presented in Figure 1-1. A detailed description of the LNG operations, including the process flow diagrams, material balances, etc., was provided for reference in this work but is not repeated in this document. Additional data used as a baseline or reference for this study are contained in Appendix C.

Non-Internet Public

DRAFT ENVIRONMENTAL IMPACT
STATEMENT/ENVIRONMENTAL IMPACT REPORT
FOR THE
LONG BEACH LNG IMPORT PROJECT

Docket No. CP04-58-000, et al.

Page 1-2
Figure 1-1

Public access for the above information is available only through the Public Reference Room, or by e-mail at public.referenceroom@ferc.gov

1.2 Scope of Study

The Port of Long Beach (POLB) retained Quest Consultants Inc. to identify the "worst-case" hazards that would result from an accidental or intentional (e.g., terrorist-induced) release of LNG in or near Sound Energy Solutions' proposed import terminal in Long Beach Harbor.

The study consisted of five primary tasks.

Task 1. Identify a range of potential releases, accidental and intentional, that could result in the largest potential impacts outside the import terminal boundary.

The POLB required the following three types of events to be evaluated . Additional events, both accidental and intentional in origin, were included following a review of project data.

Releases from an LNG tank in the import terminal

- A projectile, such as an airplane or missile, striking one or both tanks and causing a release.
- An explosive charge detonated adjacent to the tanks, causing a release.
- A release from on-site piping by any means (accidental or intentional).

Releases from an LNG tank ship at berth

- A projectile, such as an airplane or missile, striking the ship and causing a release.
- An explosive charge in a small boat detonated adjacent to the ship, causing a release.

Releases from an LNG tank ship in transit

- A grounding on, or collision with, the outer breakwater resulting in the rupture of a cargo tank.
- A collision with another vessel outside the breakwater.

Task 2. Calculate or estimate the probability of each release identified in Task 1.

Failure rate data for process equipment, tanks, and shipping transfers are available from historical data bases and industry experience for both the land-based terminal and the LNG shipping fleet. In instances where the specific release has no historical basis (i.e., an event that has never occurred during the lifetime of the industry), an estimate can be made based on the historical record of similar industries.

When estimating the probability of an intentional act resulting in a release of LNG, there is very little hard data available for review. Using historical data for a range of terrorist activities, an estimate of the probability of a terrorist attack on a flammable fuels facility in the United States can be made.

In Task 2, the mitigation systems in place that may modify the probability of an event occurring were addressed in the analysis.

Task 3. Calculate the size of the hazard zones under worst-case conditions of each release identified in Task 1.

Several consequence models were used to determine the size of the radiant energy and explosive overpressure hazard zones following a release and ignition of a flammable fluid from the LNG terminal or LNG tank ship. Four primary models or suites of models were used in the analysis. All models have limitations and restrictions. In some cases a model was modified to perform in an alternate manner than that for which it was originally intended. The models used in the analysis are:

FERC's LNG spill onto water model
LNGFIRE3
DEGADIS
CANARY by Quest®

Task 4. Determine impacts on neighboring industrial facilities due to the worst-case events

The POLB identified two crude oil berths – the existing berth at T-121 and a proposed berth at T-124 – as industrial neighbors to the LNG import terminal. In general, for LNG import terminals, the primary hazard produced by a release of LNG or other flammable fluid that would affect a neighboring industrial facility is radiation from a continuous fire. The potential radiant impacts on these and other neighboring port facilities were calculated for the releases identified in Task 1.

Task 5. Compare the LNG terminal worst-case analysis to other large-scale flammable fuel facilities

Consequence modeling results for the following large-scale flammable fuel facilities were compared to the LNG import terminal results.

Facility #1 The largest refrigerated propane terminal in northern California. This terminal has two 12,000,000-gallon refrigerated propane storage tanks and four 60,000-gallon pressurized ambient temperature storage tanks.

Facility #2 Refined petroleum tank farms, located in southern California, with large capacity storage tanks containing a variety of petroleum products.

Facility #3 A 10 million tons per annum (10 mtpa) LNG import terminal in Mexico. This terminal will have a peak natural gas generation capacity of 2.4 billion cubic feet per day (10 bcfd). Four 150,000-m^3 storage tanks will be located on site when the project is fully developed.

In addition, for comparison purposes, the flammable hazards associated with a range of LPG storage vessels were calculated. The LPG vessel sizes ranged from a 5 gallon backyard grill propane bottle to a 12,500 barrel LPG storage sphere that would be located in refinery.

1.3 Limitations of Study

The overall scope and execution of the study is limited by two necessary restrictions. First, the study is not a full quantitative risk analysis as it was designed to focus only on the largest releases. Thus, not all possible events are identified, quantified, and incorporated into the study. Instead, the events evaluated in this study cover a range of the largest accidental and intentionally-induced releases that could occur in the facility and tank ship operations. Essentially, because the study evaluates a set of representative worst-case impacts, the consequences of any event that was not specifically identified could still be expected to fall within the range described in this study.

Secondly, all the data used to develop the releases, resultant consequences, and associated probabilities are drawn from publicly available resources. No use of proprietary, confidential, or not-to-be-publicly-disclosed information was used in this study.

SECTION 2
POTENTIAL HAZARDS

2.1 Hazards Identification

Quest reviewed the preliminary design and other public information related to Sound Energy Solutions' proposed LNG Import Terminal in the Port of Long Beach. Using that information, applicable codes and standards, knowledge of and experience with similar LNG terminals, and good engineering practices, a range of large release events that have some potential to occur in the terminal was selected for analysis. In general, these large events can be divided into two categories.

(1) Large releases (ruptures), characterized by a hole with a diameter equal to the pipe diameter or, for vessels and certain process equipment, a hole with a diameter equal to the diameter of the largest attached pipe.

(2) Catastrophic failure of a vessel, characterized by a rapid release of its contents.

Potential releases of LNG, natural gas, or other hydrocarbon fluids were considered for each area within the proposed terminal, as were releases from the LNG tank ship.

2.2 Introduction to Physiological Effects of Fires and Overpressure

The consequence analysis performed for the proposed LNG terminal involved the evaluation of a range of refrigerated and superheated liquid releases, as well as releases of ambient temperature and cold natural gas. Each potential release could result in one or more of the following hazards.

- Exposure to thermal radiation from a torch fire, which is the result of ignition of a high velocity release of natural gas, LNG, or other hydrocarbons.
- Exposure to thermal radiation from a pool fire, which is the result of ignition of a pool of LNG or other hydrocarbons.
- Direct contact with flames due to a flash fire, which is the result of delayed ignition of a flammable vapor cloud following a release of natural gas, LNG, or other hydrocarbons.
- Exposure to overpressure, which may be a result of delayed ignition of a flammable vapor cloud created by a release of natural gas, LNG, or other hydrocarbons.

In order to compare the impacts associated with each type of hazard listed above, a common measure of consequence must be defined. In this study, the primary consequence of interest is the effect of the hazard on humans. For each of the fire and overpressure hazards listed above, there are benchmarks available that define these effects. The exposure levels for the various hazards are discussed in the following sections.

2.2.1 Physiological Effects of Exposure to Fires

The physiological effect of fire on humans depends on the rate at which heat is transferred from the fire to the person, and the time the person is exposed to the fire. Skin that is in contact with flames can be seriously injured even if the duration of the exposure is just a few seconds. Thus, a person wearing normal clothing is likely to receive serious burns to unprotected areas of the skin when directly exposed to the flames from a flash fire (vapor cloud fire).

People in the vicinity of a flash fire, pool fire, or torch fire, but not in contact with the flames, will receive heat from the fire in the form of thermal radiation. Radiant heat flux decreases with increasing distance from the fire, so persons close to the fire will receive thermal radiation at a higher rate than persons who are farther away. The ability of a fire to cause skin burns due to radiant heating depends on the radiant heat flux to which the skin is exposed, and the duration of the exposure. Thus, short-term exposure to high radiant heat flux levels can be injurious, but if a person is far enough from the fire, the radiant heat flux will be so low that it is incapable of causing injury, regardless of exposure time.

2.2.2 Physiological Effects of Overpressures

In the event of an ignition and deflagration of a flammable gas or aerosol cloud, the overpressure levels necessary to cause injury to people are often defined as a function of peak overpressure. Unlike potential fire hazards, persons who are exposed to overpressure have no time to react or take shelter; thus, time does not enter into the hazard relationship.

The physiological effects of overpressures depend on the peak overpressure that reaches a person. Exposure to high overpressure levels may be fatal. Persons located outside the flammable cloud when it ignites will be exposed to lower overpressure levels than persons inside the flammable cloud. If the person is far enough from the source of the overpressure, the overpressure is incapable of causing injuries.

2.2.3 Hazard Endpoint Criteria

The hazard endpoint criteria defined in this study correspond to hazard levels that might cause an injury. With this definition, the injury level is defined for each type of hazard (radiant heat or overpressure exposure). Table 2-1 presents the endpoint hazard criteria approved by the South Coast Air Quality Management District (SCAQMD) for previous work of this nature [SCAQMD, 2001].

Table 2-1
Consequence Analysis Hazard Levels
(Endpoint Criteria for Consequence Analysis)

Hazard Type	Injury Threshold		
	Exposure Duration	Hazard Level	Reference
Radiant heat exposure (torch and pool fires)	40 sec	1,600 Btu/(hr·ft^2) † [5 kW/m^2]	40 CFR 68 [EPA, 1996]
Explosion overpressure	Instantaneous	1.0 psig ‡	40 CFR 68 [EPA, 1996]
Flash fires (flammable vapor clouds)	Instantaneous	Lower Flammable Limit	40 CFR 68 [EPA, 1996]

40 CFR 68. United States Environmental Protection Agency RMP endpoints.

† Corresponds to second-degree skin burns.
‡ Corresponds to partial demolition of houses, which might cause injuries to inhabitants.

2.3 Selection of Accidental Release Case Studies Involving the LNG Terminal

The purpose of the accidental hazard case selection methodology is to define the maximum credible hazard scenarios that might result in an impact to the public. The methodology is developed in five increments:

- Initial review of available documentation
- Detailed review of process flow diagrams (PFDs)
- Development of hazard scenarios
- Screening of hazard scenarios via hazards analysis
- Final selection of hazard cases

Written descriptions of the processes were studied to determine the physical and chemical transformations occurring and the general flow of material in the facility. Process flow diagrams (PFDs) were then reviewed and compared to the written descriptions. Each of the major flow lines was evaluated individually to determine the potential for producing a major hazard if a leak or rupture occurred.

The initial selection of hazard areas considered:

- Flammability and/or toxic nature of the chemicals
- Potential for aerosol formation (releases of streams considerably above their atmospheric boiling point)
- Size of a line
- Normal flow rate in the line
- Inventory
- Severity of the process conditions

These factors were not weighted equally in the evaluation: flammability and/or toxic nature, potential for aerosol formation, and process conditions were given more weight than the other factors.

The list of potential hazard areas was constructed using the preceding analysis. The data sheet for each scenario contains the following information:

- Case number
- Description of the area where release would originate (process equipment, vessel, etc.)
- Stream number found on the PFDs
- Stream or vessel temperature
- Stream or vessel pressure
- Physical state of the stream (gas, liquid, two-phase)
- Total volume of the vessel or the nearest vessel
- Liquid volume of the vessel or the nearest vessel
- Line size
- Normal flow rate of the line or vessel

The hazard zones resulting from the worst-case releases of similar hazard scenarios were evaluated using the CANARY consequence modeling software (Section 4) to determine which ones would have the greatest potential for off-site impact (e.g., flash fire, pool fire, torch fire, overpressure).

The final selection of hazard cases was made. These selections generally defined the maximum extent of any credible potential hazard that could occur in the facility. In addition to the hazard cases selected during the analysis described above, the failure of both LNG storage tanks as a result of a severe earthquake was selected for inclusion as a possible worst-case event.

In addition to evaluating the consequences of a severe earthquake, the impact of a tsunami on the terminal was evaluated. Tsunamis are long-period oceanic waves generally caused by seismic activity. The magnitude of the potential hazard is a function of the coastline configuration, sea floor topography, individual wave characteristics, magnitude of the initiating event, and distance and direction from the source.

The largest recorded tsunami in the Long Beach or Los Angeles harbor areas had a run-up height of approximately 5 feet. This tsunami was the result of the 1960 Chile earthquake of magnitude 9.5 on the Richter scale. This is the largest recorded earthquake. Smaller tsunamis were also recorded in the area from 1812 to 1975 [McCulloch, 1985].

Various estimates of tsunami run-up heights, primarily from distant sources, have been developed for the project area. Synolakis [2003] estimated a 100-year run-up height of 8 feet and a 500-year run-up height of 15 feet for the POLB area. More recently, [Borrero, et al., 2005] estimated that a tsunami of approximately 13 feet could occur at the LNG terminal site as the result of a large, submarine landslide located 10 miles southwest of the LNG terminal site.

The tidal range in Long Beach Harbor generally varies between elevations -2 and +7 feet from mean lower low water (MLLW) elevation, with an average water level of -4.8 feet MLLW.

The surface elevation of the proposed LNG terminal site is approximately +20 to +25 feet MLLW, which is well above the estimated elevation of the 100-year tsunami (+8 feet), even if it were to occur during a very high tide. When the 500-year tsunami is considered (+15 feet), the site might experience flooding on the order of 2 feet. Therefore, a tsunami impacting the LNG terminal site is not considered an event that could cause significant plant damage.

The initial fluid conditions for the largest accidental release scenarios identified for this analysis are given in Table 2-2. For each case identified, several potential hazardous outcomes might be possible (i.e., flash fire, torch fire, pool fire, vapor cloud explosion).

2.4 Selection of Accidental Release Case Studies Involving LNG Tank Ships

A release of LNG from an LNG tank ship, either when the ship is approaching the LNG terminal or when it is berthed at the terminal, could produce hazard zones that could affect persons and property outside the boundaries of the proposed LNG terminal. Five such accident scenarios were selected for inclusion in this study.

The first set of accidental release cases for LNG ships are based on the LNG ship striking a breakwater as the ship is entering the port. If the water depth at the breakwater is sufficient, the LNG ship could strike the breakwater bow first. For the purposes of this study, it was assumed that – under certain conditions – this event could result in a release of LNG from the cargo tank nearest the bow of the ship, which might escalate until it involved all cargo tanks on the ship. Groundings in the approach area (precautionary zone and main channel) to the Port of Long Beach or in the Port waters were not considered credible events.

Table 2-2
Initial Fluid Conditions for Selected Accidental Release Scenarios; LNG Terminal

Description	Fluid Temperature (EF)	Fluid Pressure (psia)	Fluid State	Normal Flow Rate (lb/sec)
Rupture of process equipment - location A*	-252.8	109.6	Liquid	4,773.0
Rupture of process equipment - location B*	-248.6	116.0	Liquid	75.0
Rupture of process equipment - location C*	-167.3	567.2	Liquid	60.7
Rupture of process equipment - location D*	-121.2	735.0	Liquid	121.4
Rupture of process equipment - location E*	54.8	689.9	Gas	364.1
Release from process equipment - location F*	123.4	579.8	Liquid	76.0
Release from process equipment - location G*	-9.4	207.0	Liquid	75.2
Release from LNG storage tanks following earthquake	-254.0	16.7	Liquid	—

* Details have been removed because this is considered to be Critical Energy Infrastructure Information (CEII)[1] by the FERC

Another such accident is a collision involving an LNG tank ship and another ship. Under certain conditions, a collision could have the potential to cause a release of LNG from one or more of the cargo tanks on the LNG ship. Thus, the loss of LNG from one cargo tank, as the result of a collision, was included in the analysis. For the purposes of this study, it was assumed that – under certain conditions – this event could result in a release of LNG from the cargo tank nearest the bow of the ship, which might escalate until it involved all cargo tanks on the ship.

If an LNG tank ship were to be unloading when a 500-year tsunami were to occur, the ship could elevate up to 15 feet. The ship's motion would result in several responses. First, the Powered Emergency Release Couplings (PERCs) on the loading arm would close due to the arms moving outside of their envelope of operation. This would result in a release of a few liters of LNG (fluid between the closed valves). A second result could be the breaking of the mooring lines due to the ship's elevation. At this point, the ship may hit another structure, ground on an object, or be hit by another ship. In all instances, the consequences associated with these events would be no larger than those evaluated in the scenarios described above involving ship collisions, etc.

2.5 Selection of Intentional Release Case Studies

Selecting releases that could be intentionally created by one or more persons required a different approach than that used to define accidental releases. Accidental releases are defined as those that:

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[1]Critical Energy Infrastructure Information (CEII) Defined:

CEII is information concerning proposed or existing critical infrastructure (physical or virtual) that:

1. *Relates to the production, generation, transmission or distribution of energy;*
2. *Could be useful to a person planning an attack on critical infrastructure;*
3. *Is exempt from mandatory disclosure under the Freedom of Information Act; and*
4. *Gives strategic information beyond the location of the critical infrastructure.*

- have occurred in an LNG facility, or
- have occurred in an industry using similar types of equipment, or
- could reasonably be argued could occur in an LNG facility.

Conversely, selecting intentionally created releases of LNG or natural gas, due to sabotage or terrorism, requires a broader, more creative approach. In order to define a representative list of intentionally created releases, the following factors were considered.

- The primary target of the action (based on inventory, accessability, location, etc.)
- The obstacles to overcome in order to effect a release from the target

It is important to recognize the distinction between selecting accidental release scenarios and selecting intentional release scenarios. It is best summarized by the following statements.

- Accidental release scenarios are based on credible events, but not incredible events.
- Intentional release scenarios are based on possible events, but not impossible events.

The distinction between these selection criteria is critical to understanding the basis of the following analysis. Credible events are often defined as those that have some reasonable probability of occurring. This probability is often based on the historical record of the industry (and similar industries) and is often described in numerical and qualitative terms. For example, a release that might occur once in the lifetime of a facility would be considered a credible accidental event. One example of how qualitative descriptions can be associated with numerical values is presented in Table 2-3 [EN1473, 1997].

In general, releases that have the possibility to occur, but are considered to have a very low probability of occurrence, are not considered in an accidental analysis. These events may be defined as incredible. An example would be the failure of an LNG storage tank because it was hit by a meteorite. The probability is not zero, it is simply very, very low.

A second class of events that have a non-zero probability of occurrence, but a higher probability than that associated with being hit by a meteorite, might not be included in an accidental release analysis because their probabilities are below a predefined value. For example, if the probability of an event is less than 1.0×10^{-6} per year, it might be excluded from an accidental analysis. When this approach is taken, some large consequence/low probability events are excluded from an accidental analysis. An example of this would be the accidental crash of a commercial jet into the LNG terminal. As with the meteorite example, the probability of this event is not zero, it is simply so low that it is not often considered a credible event.

When discussing intentional acts, it may not be possible to assign a numerical value to the probability of a specific intentional act. In light of this, the discussion changes from credible/incredible to possible/impossible. In the following section, several intentional events are described. The descriptions include discussion of various obstacles that might need to be overcome in order to effect a release from the LNG terminal. In each case, the sequence of events and the final outcome are defined as possible. This does not mean they are likely or even credible, they are simply possible.

Using this definition - that an intentional event is simply possible - the following events have been identified for evaluation.

Table 2-3
Probabilities Ranges

Range	*Description*	*Probability of Occurrence*
1	*Frequent or quasi-certain event.*	*more than 10^{-2}/year*
2	*Possible but not very frequent event.*	*10^{-2} up to 10^{-4}/year*
3	*Rare Event.*	*10^{-4} up to 10^{-6}/year*
4	*Extremely rare event.*	*10^{-6} up to 10^{-8}/year*
5	*Improbable event.*	*less than 10^{-8}/year*
6	*Event of non-quantifiable probability (falling of mete-orite, attempt on life or property, etc.).*	*Unknown*

2.5.1 Identification of Primary Targets of an Intentional Event

The LNG import terminal is divided into three main operations; LNG storage, LNG and natural gas liquids processing, and LNG transport by tank ship. Using these three operations as a guide, the following intentional release base scenarios were identified as possible.

Table 2-4
Intentional Release Scenarios

Target	Mechanism to effect release of LNG, natural gas, or other hydrocarbon
LNG Storage Tank	Crash of commercial jet Truck bomb near base of storage tank Rocket-propelled grenade
LNG Process Equipment	Satchel charge placed by equipment
LNG Tank Ship	Crash of commercial jet Boat bomb while tank ship is docked Rocket-propelled grenade Collision with another ship

These eight intentional base events cover a range of potential impacts, as well as a varying degree of difficulty in regard to effecting a release of LNG, natural gas, or other hydrocarbons. This list is not intended to identify all possible intentional (terrorist or sabotage) events. It does represent a range of events, all of which are possible to some degree, but many of which are extremely unlikely simply due to obstacles that would need to be overcome by the perpetrators.

2.5.2 Description of Intentional Release Events

A description of how each of the listed intentional events might unfold is provided below. At several points in each scenario, several possible actions are listed. Generally, only one of the possible actions allows the sequence of events to proceed toward effecting a release from the target. This action is presented in italics in each event sequence table.

In most cases, it is impossible to define or calculate a specific conditional probability for each potential action choice. For instance, assuming a commercial jet is successfully highjacked following take off, and that the highjackers intend to crash the plane into one of the LNG storage tanks, what is the probability that the plane will be shot down by the U.S. military? Such values cannot be known, although it is reasonable to assume that the probability is not 100%.

The descriptions of intentional release events end with the release of LNG, natural gas, or flammable hydrocarbons from the facility. The development of the probability of a successful intentional act is presented in Section 3. Calculations of the magnitude and potential impacts of a release of LNG, natural gas, or other hydrocarbons following the listed intentional acts are presented in Section 4.

The list of intentional events is not meant to be all-inclusive, rather it is meant to span the range of intentional events that can be described as possible for the LNG terminal.

2.5.2.1 Crash of Commercial Jet into LNG Storage Tanks

The premise behind this intentional event is that one or more individuals commandeer a commercial jet and crash the plane into the LNG facility with the intention of hitting one or both of the LNG storage tanks.

Table 2-5
Terrorist-Hijacked Aircraft Crashing into One or both LNG Tanks

Action	Notes
Terrorists avoid airport security	
Unsuccessful - terrorists stopped; flight canceled or delayed *Successful - terrorists board aircraft*	There have been approximately 30 million commercial flights (U.S. carriers) in the US since September 11, 2001, without a hijacking. [NTSB, 5]
Terrorists commandeer the aircraft	
Unsuccessful - aircraft lands Unsuccessful - aircraft crashes *Successful - aircraft commandeered*	Post- September 11, 2001, additional in-flight security measures (e.g., Air Marshals, cockpit doors) have been added to impede hijacking. *Assume* Boeing 767 is the hijacked aircraft.
Aircraft eludes US Air Force	
Unsuccessful - aircraft forced to land Unsuccessful - aircraft shot down *Successful - aircraft continues toward Long Beach*	Whether this will be effective depends on response time and clarity of threat.

Table 2-5
Terrorist-Hijacked Aircraft Crashing into One or both LNG Tanks
(Continued)

Action	Notes
Terrorists hit the side of tank with aircraft	
Unsuccessful - aircraft misses tank(s) altogether, crashes nearby Unsuccessful - aircraft is too high, hits top of tank, and does not breach tank walls *Successful - aircraft hits side of tank*	Flying very low to the ground at high speed in a large jet takes considerable skill and there is a small margin for error. The LNG tanks are "small" targets in comparison to the World Trade Center or the Pentagon.
One jet engine hits side of LNG storage tank	
Unsuccessful - aircraft's jet engines do not hit tank wall *Successful - one of the aircraft's jet engines does hit side of tank wall*	Aircraft bodies, with the exception of a few parts like the engines, are "soft" in comparison to the full containment tank walls. Note that significant aircraft debris did not exit the World Trade Center buildings. Only the jet engine core is considered capable of penetrating full containment tank wall. Jet engines can hit only one LNG storage tank since the engines are approximately 50 feet apart and the LNG storage tanks are spaced approximately 120 feet apart (shell-to-shell). There is no mechanism for each engine to hit a different LNG tank at a near perpendicular angle.
Jet engine hits tank at near perpendicular angle	
Unsuccessful - aircraft's jet engine(s) hit tank wall at obtuse angle *Successful - one of the aircraft's jet engines hits tank wall at an angle such that the tank wall is penetrated*	If an engine does not hit the tank wall at a near perpendicular angle, the engine may deflect off the tank wall. If the aircraft engine is assumed to be a solid projectile (a conservative assumption), then impact analysis on the tank wall will determine whether the engine can penetrate the tank wall.

2.5.2.2 Detonation of Truck Bomb by the Base of an LNG Storage Tank

The premise behind this intentional act is that one or more individuals drive a moderate sized truck containing explosives into the LNG facility, park the truck by one of the LNG storage tanks, then detonate the explosives.

Table 2-6
Terrorist Detonates Truck Bomb Near LNG Tank

Action	Notes
Terrorists avoid POLB security	
Unsuccessful - terrorists stopped, truck confiscated *Successful - entrance to POLB*	To be successful, the terrorists must either avoid or neutralize POLB security.
Terrorists avoid SES security	
Unsuccessful - terrorists stopped, truck confiscated *Successful - entrance into SES LNG terminal; terrorists drive truck toward LNG tank area*	To be successful, the terrorists must either avoid or neutralize SES security.
Terrorists drive truck over impoundment wall toward tanks	
Unsuccessful - unable to drive truck over impoundment wall *Successful - truck enters impoundment area*	Security wall is approximately 20-ft tall. Vehicular access to the area bounded by the security wall is limited to one sloped roadway.
Terrorists park truck very near LNG tank wall	
Unsuccessful - truck cannot be parked close enough to LNG tank *Successful - truck parked against or very close to LNG tank wall*	Tank layout will determine how close a truck can approach an LNG tank.
Terrorists detonate explosives in truck	
Unsuccessful - explosives fail to detonate *Successful - explosives detonate*	Small probability that detonation will not take place.

2.5.2.3 Firing a Rocket-propelled Grenade Into an LNG Storage Tank

The premise behind this intentional act is that one or more individuals fire a rocket-propelled grenade (RPG) at one of the LNG storage tanks.

Table 2-7
Terrorist Fires Rocket-propelled Grenade (RPG) Into One or both LNG Tanks

Action	Notes
Scenario A - Land-based approach	
Terrorists avoid POLB security	
Unsuccessful - terrorists stopped; RPGs confiscated *Successful - proceed to LNG facility*	To be successful, the terrorists must either avoid or neutralize POLB security.
Terrorists avoid SES security	
Unsuccessful - terrorists stopped; RPGs confiscated *Successful - enters SES LNG terminal grounds and moves toward LNG tank area*	To be successful, the terrorists must either avoid or neutralize SES security.
Terrorists hit LNG tank with RPG	
Unsuccessful - RPG misses tank Unsuccessful - RPG hits tank at an oblique angle and does not penetrate concrete wall *Successful - RPG hits tank at near perpendicular angle and penetrates concrete wall.*	
Scenario B - Water-based approach	
Terrorists avoid POLB, City of Long Beach (COLB), and United States Coast Guard (USCG) security	
Unsuccessful - terrorists stopped; RPGs confiscated *Successful - enters West Basin*	To be successful, the terrorists must either avoid or neutralize three levels of non-project security.
Terrorists avoid SES security	
Unsuccessful - terrorists stopped; RPGs confiscated *Successful - enters SES LNG terminal grounds and moves toward LNG tank area*	To be successful, the terrorists must either avoid or neutralize SES security.
Terrorists hit LNG tank with RPG	
Unsuccessful - RPG misses tank Unsuccessful - RPG hits tank at an oblique angle and does not penetrate concrete wall *Successful - RPG hits tank at near perpendicular angle and penetrates concrete wall.*	

2.5.2.4 Detonation of Satchel Charge by Process Equipment

The premise behind this intentional act is that one or more individuals place small explosive charges (satchel charges) next to one or more pieces of equipment in the LNG terminal.

Table 2-8
Terrorist Detonates Satchel Charge by Equipment

Action	Notes
Terrorists avoid POLB security	
Unsuccessful - terrorists stopped, explosives confiscated *Successful - entrance to POLB*	To be successful, the terrorists must either avoid or neutralize POLB security.
Terrorists avoid SES security	
Unsuccessful - terrorists stopped, explosives confiscated *Successful - terrorists enter SES LNG terminal and proceed to LNG equipment area*	To be successful, the terrorists must either avoid or neutralize SES security.
Terrorists place satchel charge very near important LNG equipment	
Unsuccessful - choose minor equipment as target Unsuccessful - satchel charge placed too far away from important equipment to cause a failure *Successful - satchel charge placed against or very close to important LNG equipment*	Assumes terrorists know which equipment would produce a significant hazard if damaged.
Terrorists detonate satchel charge	
Unsuccessful - explosives fail to detonate *Successful - explosives detonate, resulting in failure of LNG equipment (e.g. pipe, pump)*	Small probability that detonation will not take place.

2.5.2.5 Crash of Commercial Jet Into LNG Tank Ship While at LNG Terminal

The premise behind this intentional event is that one or more individuals commandeer a commercial jet and crash the plane into an LNG tank ship while it is docked at the terminal. The required sequence of events for this act is similar to those for crashing a commercial jet into the LNG storage tanks.

Table 2-9
Terrorist-Hijacked Aircraft Crashing Into Berthed LNG Tank Ship

Action	Notes
Terrorists avoid airport security	
Unsuccessful - terrorists stopped, flight canceled *Successful - terrorists board aircraft*	There have been approximately 30 million commercial flights (U.S. carriers) in the US since September 11, 2001, without a hijacking. [NTSB, 5]

Table 2-9
Terrorist-Hijacked Aircraft Crashing Into Berthed LNG Tank Ship
(Continued)

Action	Notes
Terrorists commandeer the aircraft	
Unsuccessful - aircraft lands Unsuccessful - aircraft crashes *Successful - aircraft commandeered*	Post- September 11, 2001, additional in-flight security measures (e.g., Air Marshals, cockpit doors) have been added to impede hijacking. *Assume* Boeing 767 is the hijacked aircraft.
Aircraft eludes US military	
Unsuccessful - aircraft forced to land Unsuccessful - aircraft shot down *Successful - aircraft continues toward Long Beach*	Whether this will be effective depends on response time and clarity of threat.
Aircraft approaches loaded LNG tank ship at berth	
Unsuccessful - LNG tank ship is not berthed Unsuccessful - LNG tank ship at berth, but contains little cargo *Successful - loaded LNG tank ship is berthed at terminal*	The LNG tank ship may not be at berth or it may be nearly empty and at the end of its unloading operation.
Terrorists hit the LNG tank ship with aircraft	
Unsuccessful - aircraft is too high and misses LNG tank ship altogether Unsuccessful - aircraft is too low and crashes before hitting LNG tank ship *Successful - aircraft hits side or top of LNG tank ship*	Flying very low to the ground at high speed in a large jet takes considerable skill and there is a small margin of error. LNG tank ships are "small" targets in comparison to the World Trade Center or the Pentagon

2.5.2.6 Detonation of Boat Bomb Near the LNG Tank Ship While at LNG Terminal

The premise behind this intentional act is that one or more individuals pilot a small boat containing explosives up to the LNG tank ship while it is docked at the LNG facility, then detonate the explosives.

Table 2-10
Terrorists Place Boat Bomb Beside LNG Tank Ship

Action	Notes
Terrorists avoid POLB, COLB, and USCG security	
Unsuccessful - terrorists stopped, explosives confiscated *Successful - enters West Basin*	To be successful, the terrorists must either avoid or neutralize three levels of non-project security.
Terrorists avoid SES security	
Unsuccessful, terrorists stopped, explosives confiscated *Successful - approaches LNG tank ship mooring area*	To be successful, the terrorists must either avoid or neutralize SES security.
Terrorists detonate bomb	
Unsuccessful - explosives do not go off Unsuccessful - explosives set off too far from LNG tank ship to damage outer hull Unsuccessful - explosives set off such that outer hull is breeched, but inner hull is not breached *Successful - outer hull, inner hull, and cargo tank breeched by blast*	How close the boat bomb must be to the ship depends on the "size" of the bomb.

2.5.2.7 Firing an RPG Into an LNG Tank Ship While at LNG Terminal

The premise behind this intentional act is that one or more individuals fire an RPG at the LNG tank ship while it is docked at the LNG facility.

Table 2-11
Terrorist Fires Rocket-propelled Grenade (RPG) Into LNG Tank Ship

Action	Notes
Scenario A - Land-based approach	
Terrorists avoid POLB security	
Unsuccessful - terrorists stopped; RPGs confiscated *Successful - entrance to POLB*	To be successful, the terrorists must either avoid or neutralize POLB security.

Table 2-11
Terrorist Fires Rocket-propelled Grenade (RPG) Into LNG Tank Ship
(Continued)

Action	Notes
Terrorists hit LNG tank ship with RPG	
Unsuccessful - RPG misses tank ship Unsuccessful - RPG hits deck at an oblique angle and does not penetrate deck Unsuccessful - RPG hits outer hull of tank ship at an oblique angle and does not penetrate hull Unsuccessful - RPG hits outer hull of tank ship at near perpendicular angle and penetrates outer hull but not inner hull *Successful - RPG hits outer hull of tank ship at near perpendicular angle and penetrates outer hull and inner hull.*	
Scenario B - Water-based approach	
Terrorists avoid POLB, COLB, and USCG security	To be successful, the terrorists must either avoid or neutralize three levels of non-project security.
Unsuccessful - terrorists stopped; RPGs confiscated *Successful - enters West Basin*	
Terrorists avoid SES security	To be successful, the terrorists must either avoid or neutralize SES security.
Unsuccessful - terrorists stopped; RPGs confiscated *Successful - entrance into water near LNG tank ship*	
Terrorists hit LNG tank ship with RPG	
Unsuccessful - RPG misses tank ship Unsuccessful - RPG hits outer hull of tank ship at an oblique angle and does not penetrate outer hull Unsuccessful - RPG hits outer hull of tank ship at near perpendicular angle and penetrates outer hull but not inner hull *Successful - RPG hits outer hull of tank ship at near perpendicular angle and penetrates outer hull and inner hull*	

2.5.2.8 Terrorist Controlled Ship Collides with LNG Tank Ship

The premise behind this intentional event is that one or more individuals commandeer a ship and cause it to collide with an LNG tank ship.

Table 2-12
Terrorist-Controlled Ship Collides with LNG Tank Ship

Action	Notes
Terrorists commandeer a ship	
Unsuccessful - terrorists stopped by crew or USCG *Successful -terrorists gain control of ship.*	Terrorists would need to overcome crew before crew could contact USCG.
Terrorists sail ship toward full LNG tank ship	
Unsuccessful - USCG foils attempt before LNG ship arrives Unsuccessful - terrorists lack the knowledge needed to control the ship *Successful - terrorist-controlled ship on collision course with LNG tank ship*	To increase the odds of success, the terrorists would need to avoid being detected by the USCG and would need to calculate successful course.
Terrorist-controlled ship collides with full LNG tank ship	
Unsuccessful - error by terrorists causes their ship to miss LNG tank ship Unsuccessful - evasive maneuvers by LNG tank ship result in near miss *Successful - ships collide, causing damage to both ships*	
Collision between terrorist-controlled ship and LNG tank ship results in failure of one LNG cargo tank	
Unsuccessful - terrorist ship does not hit the cargo section of LNG ship Unsuccessful - momentum of terrorist ship not sufficient to cause failure of a cargo tank Unsuccessful - terrorist ship strikes LNG ship at an angle too far from perpendicular and does not penetrate outer hull *Successful - bow of terrorist-controlled ship penetrates outer hull, inner hull, and cargo tank wall of LNG tank ship*	

SECTION 3
DEVELOPMENT OF INCIDENT PROBABILITIES

3.1 Accidental Releases of LNG, Natural Gas, or Other Hydrocarbon Fluids in the LNG Terminal

The probability of occurrence of an accident that results in the release of LNG, natural gas, or hydrocarbon fluids is typically based on the historical record of occurrence of such accidents, or similar accidents involving similar equipment and materials. This commonly used technique is valid for accidents (unintentional events) because they are random events.

The likelihood of a particular accident occurring within some specific time period can be expressed in different ways. One way is to state the statistical probability that the accident will occur during a one-year period. This annual probability of occurrence can be derived from failure frequency data bases of similar accidents that have occurred with similar systems or components in the past.

Most data bases (e.g., CCPS [1989b], OREDA [1984]) that are used in this type of analysis contain failure frequency data (e.g., on the average, there has been one failure of this type of equipment for 347,000 hours of service). By using the following equation, the annual probability of occurrence of an event can be calculated if the frequency of occurrence of the event is known.

$$p = 1 - e^{(-\lambda \cdot t)}$$

where:

p = annual probability of occurrence (dimensionless)
λ = annual failure frequency (failures per year)
t = time period (one year)

If an event has occurred once in 347,000 hours of use, its annual failure frequency is computed as follows.

$$\lambda = \frac{1\ \text{event}}{347{,}000\ \text{hours}} \cdot \frac{8{,}760\ \text{hours}}{\text{year}} = 0.0252\ \text{events/year}$$

The annual probability of occurrence of the event is then calculated as follows.

$$p = 1 - e^{(-0.0252 \cdot 1)} = 0.0249$$

Note that the frequency of occurrence and the probability of occurrence are nearly identical. (This is always true when the frequency is low.) An annual probability of occurrence of 0.0249 is approximately the same as saying there will probably be one event per forty years of use.

Due to the scarcity of accident frequency data bases, it is not always possible to derive an exact probability of occurrence for a particular accident. Also, variations from one system to another (e.g., differences in design, construction, operation, maintenance, or mitigation measures) can alter the probability of occurrence for a specific system. Therefore, variations in accident probabilities are usually not significant unless the variation approaches one order of magnitude (i.e., the two values differ by a factor of ten).

In developing the accidental probabilities for the largest accidental releases of LNG, natural gas, and other hydrocarbons identified in Section 2, the references in Appendix A were used.

3.1.1 Example – Development of Event Tree for an Accidental Release from LNG Process Equipment

A release of LNG into the atmosphere may create one or more hazardous conditions, depending on events that occur subsequent to the release. For a fluid such as LNG that is flammable but not toxic, the possibilities are:

(a) No ignition. If a flammable vapor cloud forms but never ignites, the cloud dissipates.

(b) Immediate ignition. If ignition occurs nearly simultaneously with the beginning of the release, the hazard may be thermal radiation from a torch fire (pressurized release) or pool fire (nonpressurized release), or both in some instances.

(c) Delayed ignition with no significant overpressure generated. If there is a time delay between the start of the release and ignition of the release, a flammable vapor cloud will form. After ignition, there will be a vapor cloud fire (flash fire), possibly followed by a pool fire or torch fire.

(d) Delayed ignition with explosion. This situation is just like the previous case but, subsequent to ignition, the vapor cloud explodes rather than burns. The strength of the overpressure developed during the explosion will be dependent on the degree of congestion in the area. Congestion is defined by the amount of void space (open air) in the volume occupied by the equipment, etc., in the area. As rule of thumb, low congestion would be defined as 90% void space (10% equipment) and high congestion would be defined as less than 40% void space.

Each of these four possibilities has some probability of occurring, once a release has occurred. The sum of these four probabilities must equal one. The ignition/explosion probabilities employed in this study are taken from an Institution of Chemical Engineers report [Cox, Lees, and Ang, 1990]. The probabilities are a function of the size of the release.

Consequences of the hazardous events that may occur after release of LNG are proportional to the size of the release. Therefore, when calculating the final outcome probability, it is necessary to estimate the distribution of releases of various sizes. This is typically done by applying a hole size distribution. Information on hole size distributions is included in the data bases listed in Appendix A.

The calculations made for hole size and ignition probability are best illustrated by event trees. One of the event trees prepared for this study is presented in Figure 3-1. It begins with the release of LNG from process piping. Moving from left to right, the tree first branches into three release sizes, each being defined by the diameter (d) of the hole through which the fluid is being released. Each of these three branches divides into three branches based on ignition timing and probability. Each delayed ignition branch divides again into two branches: flash fire and vapor cloud explosion (VCE). At the far right of the event tree are the twelve "outcomes" that have some probability of occurring if the initiating release occurs.

To arrive at the probability of a specific outcome, the probability of failure of the process equipment is modified by the probability at each applicable branch of the event tree. The estimated annual probability of occurrence of each possible outcome, per foot of pipe, is listed on the event tree. For example, the probability of an immediate torch fire following a rupture of the piping leading to piece of process equipment can be found by starting with the probability of a failure per foot of pipe per year ($4.5\ (10)^{-8}$ ft/yr and multiplying it by the percent of time the failure would be a rupture (5.6%), then multiplying it by the percent of time the release is immediately ignited (10%). This is calculated as:

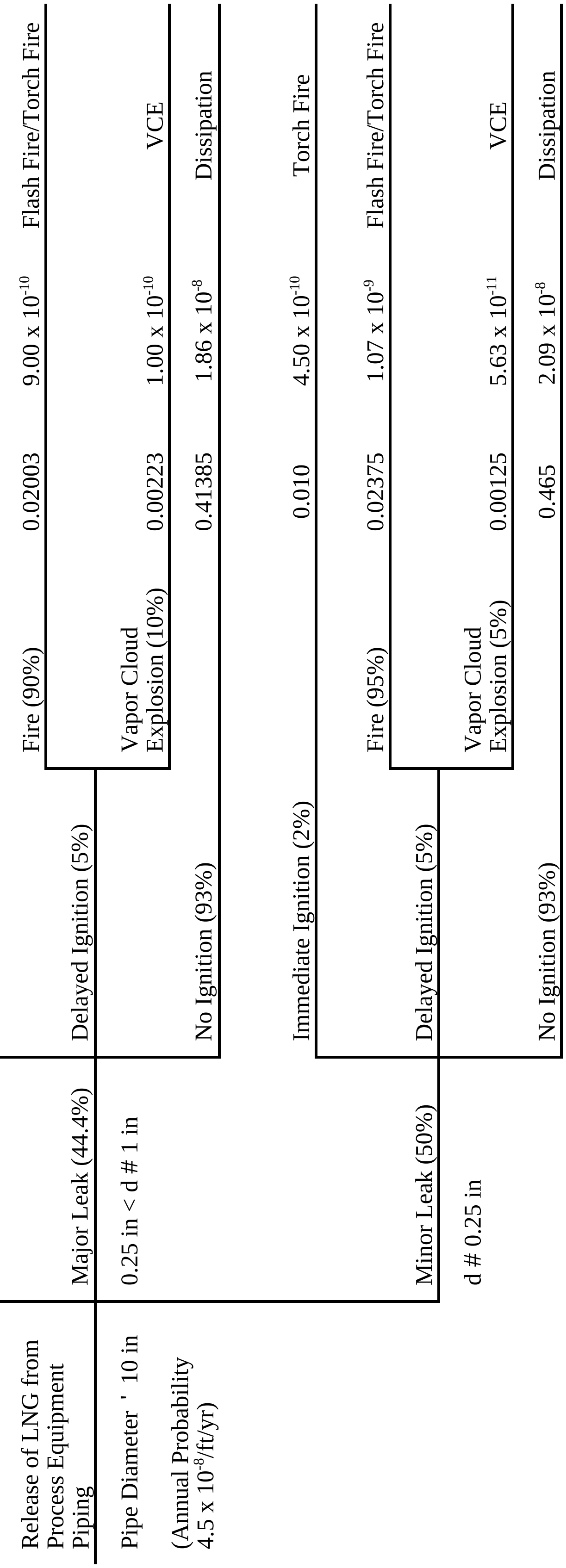

Figure 3-1
Example Event Tree for a Release of LNG from Process Equipment Piping

$$4.5\left(10^{-8}\right)/\text{ft/yr} \cdot 0.056 \cdot 0.10 = 2.5\left(10^{-10}\right)/\text{ft/yr}$$

This value is then multiplied by the amount of piping (x feet) in order to arrive at the total probability of a rupture in the piping associated with the piece of process equipment that results in an immediate torch fire.

In general, small releases are the most likely to occur, the least likely to be ignited (small probability of reaching an ignition source), and least likely to result in vapor cloud explosions (insufficient mass of gas in the flammable gas cloud). The largest releases are the least likely to occur, the most likely to be ignited (highest probability of reaching an ignition source), the most likely to be ignited immediately (the force needed to cause a large release may also be capable of igniting the release), and the most likely to result in a vapor cloud explosion (highest probability of being partially confined by obstructions).

Since the conditional probabilities for ignition and explosion in the event tree are not derived from an historical data base, it could be argued that these probabilities should be increased or decreased. However, even large changes (50%) in the individual probabilities will not make a significant change in the overall analysis since increasing the probability of one event results in a decrease in the probability of some other event.

Similar event trees were constructed for all the accidental LNG, natural gas, and other hydrocarbon releases listed in Table 2-2 (with the exception of the LNG storage tanks failing as the result of an earthquake, which is discussed in Section 3.2). The final outcome probabilities of the largest releases (e.g., full ruptures) identified are presented in Table 3-1.

Table 3-1
Accidental Release and Final Outcome Probabilities

Release Description	Probability of Rupture	Outcome	Outcome Probability	Once In
Rupture of process equipment - location A *	9.45×10^{-7} / yr	Immediate Torch/Pool Fire Delayed Torch/Pool Fire Flash Fire Vapor Cloud Explosion Dissipation	9.45×10^{-8} / yr 1.32×10^{-7} / yr 1.32×10^{-7} / yr 5.67×10^{-8} / yr 6.61×10^{-7} / yr	10,660,000 yr 7,570,000 yr 7,570,000 yr 17,600,000 yr 1,510,000 yr
Rupture of process equipment - location B *	6.69×10^{-5} / yr	Immediate Torch/Pool Fire Delayed Torch/Pool Fire Flash Fire Vapor Cloud Explosion Dissipation	6.69×10^{-6} / yr 9.36×10^{-6} / yr 9.36×10^{-6} / yr 4.01×10^{-6} / yr 4.68×10^{-5} / yr	149,000 yr 107,000 yr 107,000 yr 249,000 yr 21,400 yr
Rupture of process equipment - location C *	6.60×10^{-5} / yr	Immediate Torch/Pool Fire Delayed Torch/Pool Fire Flash Fire Vapor Cloud Explosion Dissipation	6.60×10^{-6} / yr 9.24×10^{-6} / yr 9.24×10^{-6} / yr 3.96×10^{-6} / yr 4.62×10^{-5} / yr	151,000 yr 108,000 yr 108,000 yr 252,000 yr 21,600 yr
Rupture of process equipment - location D *	5.28×10^{-5} / yr	Immediate Torch/Pool Fire Delayed Torch/Pool Fire Flash Fire Vapor Cloud Explosion Dissipation	5.28×10^{-6} / yr 9.40×10^{-6} / yr 9.40×10^{-6} / yr 3.17×10^{-6} / yr 3.70×10^{-5} / yr	189,000 yr 106,000 yr 106,000 yr 315,000 yr 27,000 yr

Table 3-1
Accidental Release and Final Outcome Probabilities
(Continued)

Release Description	Probability of Rupture	Outcome	Outcome Probability	Once In
Rupture of process equipment - location E *	4.05×10^{-6} / yr	Immediate Torch/Pool Fire Delayed Torch/Pool Fire Flash Fire Vapor Cloud Explosion Dissipation	4.05×10^{-7} / yr 7.29×10^{-7} / yr 7.29×10^{-7} / yr 8.10×10^{-8} / yr 2.83×10^{-6} / yr	2,470,000 yr 1,370,000 yr 1,370,000 yr 12,300,000 yr 353,000 yr
Release from process equipment - location F *	3.80×10^{-6} / yr	Immediate Torch/Pool Fire Delayed Torch/Pool Fire Flash Fire Vapor Cloud Explosion Dissipation	3.80×10^{-7} / yr 5.32×10^{-7} / yr 5.32×10^{-7} / yr 2.28×10^{-7} / yr 2.66×10^{-6} / yr	2,630,000 yr 1,880,000 yr 1,880,000 yr 4,390,000 yr 376,000 yr
Release from process equipment - location G *	4.79×10^{-6} / yr	Immediate Torch/Pool Fire Delayed Torch/Pool Fire Flash Fire Vapor Cloud Explosion Dissipation	4.79×10^{-7} / yr 6.71×10^{-7} / yr 6.71×10^{-7} / yr 2.88×10^{-7} / yr 3.35×10^{-6} / yr	2,090,000 yr 1,490,000 yr 1,490,000 yr 3,470,000 yr 298,000 yr

* Details have been removed because this is considered to be Critical Energy Infrastructure Information (CEII) by the FERC

3.2 Accidental Releases of LNG from LNG Storage Tanks and Tank Ships

3.2.1 Earthquake-induced Failure of Both LNG Storage Tanks

Like all structures built from metal and concrete, LNG storage tanks can be damaged by a seismic event (earthquake) if the earthquake is strong enough to produce ground accelerations that exceed the limits of the structure. A research and consulting agency established by the government of the Netherlands (Netherlands Organization for Applied Scientific Research, commonly referred to as TNO) has estimated the probability of an accidental instantaneous release of the contents of a full-containment storage tank to be 1×10^{-8} per year [TNO, 1999]. In the absence of historical data for earthquake-induced failures of full-containment storage tanks (i.e., no such failure has ever been recorded for an LNG storage tank), 1×10^{-8} is often referenced within a study to represent the annual probability that a full containment LNG tank could fail.

Site-specific studies [ARUP, 2005, KBR, 2005, and URS/KBR, 2005] for the proposed LNG import terminal in the POLB found three faults within seven km of the proposed terminal. An analysis of the structural design of the LNG tanks found that a peak ground acceleration greater than 1.14 g would be required at the LNG tank location before the forces on the tank might initiate a failure. In order for the Palos Verdes fault (four km away) to produce a peak ground acceleration of 1.14 g or higher, an earthquake exceeding 9 on the Richter scale would be required. This fault is considered "unrealistic" in the seismic assessment [KBR, 2005] that determined that the frequency of such an earthquake would be once in 20,000 years (5×10^{-5} per year). The two remaining faults in the area; Newport-Inglewood and THUMBS-HB were determined to not be capable of producing an earthquake that would produce the peak ground accelerations at the site that may cause tank failure.

Using the site-specific analysis performed for the proposed POLB full containment tanks, the failure of one or both tanks due to an earthquake has been defined as *credible* for this work (i.e., the failure frequency is greater than $1x(10)^{-6}$ per year). Using the LNG-specific EN1473 frequency definitions (see Table 2-3), the failure of one or both LNG tanks due to an earthquake would fall in Range 3, a *Rare Event*. The State of California's Risk Management Program (RMP) requires the evaluation of hazardous material releases that are defined as *probable*. In applying the RMP definitions to hazardous material releases, the Los Angeles County Fire Department's guidelines (LACFD, 1991) define the following categories of probability of occurrence of a hazardous material release.

Frequent	=	More than once a year (> $1x(10)^{0}$ per year).
Periodic	=	Once every 1 to 10 years ($1x(10)^{0}$ to $1x(10)^{-1}$ per year). At least once each decade.
Occasional	=	Once every 10 to 100 years ($1x(10)^{-1}$ to $1x(10)^{-2}$ per year). Probably during the life of the project..
Possible	=	Once every 100 to 10,000 years ($1x(10)^{-2}$ to $1x(10)^{-4}$ per year). Not expected, but could occur.
Improbable	=	Not for 10,000 or more years (< $1x(10)^{-4}$ per year). Not expected or likely to occur at all.

The consequences associated with an earthquake-induced failure of one or both LNG storage tanks will be included in the following worst-case consequence analysis because they are *credible*. However, the failure of one or both tanks due to an earthquake is defined as *improbable* per the State of California RMP guidelines and would not be included in an RMP consequence evaluation.

3.2.2 Release of LNG from Ship's Cargo Tank as a Result of Colliding with the Breakwater

If an LNG tank ship were to strike a massive fixed object at sufficient speed, there is a possibility that the impact could result in a release of LNG from a cargo tank (most likely the tank nearest the bow). A study of the mechanics of LNG ship collisions [Greuner and Böckenhauer, 1980] concluded that if a 125,000 m^3 LNG tank ship were to strike a jetty, a "dangerous situation" would occur only if the ship was moving at a speed of more than 10 knots at the time it hit the jetty. It is expected that LNG tank ships will be moving at speeds lower than 10 knots when in the vicinity of the breakwater in the POLB.

According to the Los Angeles/Long Beach Harbor Safety Plan [POLB, 2004], the vessel speed limits in the precautionary zone (outside the breakwater but inside the Sierra and Whiskey buoys) is 12 knots. The vessel speed limit in the Main Channel is 10 knots and the vessel speed limit everywhere else in the Port is 6 knots.

According to industry records [GIIGNL, 2003], there have been approximately 40,000 loaded voyages of LNG tank ships since the commercial marine transport of LNG began in 1959. Since split cargoes (i.e., unloading part of the cargo at one terminal and the rest of it at another terminal) are rare in the LNG trade, it can be assumed that 40,000 ballast voyages (i.e., voyages with the cargo tanks being nearly empty) have also been completed by LNG tank ships. Combining loaded voyages and ballast voyages, and assigning one port call for each voyage (either to be loaded or to be unloaded), results in approximately 80,000 port calls. Thus, there have been about 80,000 chances for an LNG ship to strike a fixed object while in or near a port. Two such incidents have been reported [*Hazardous Cargo Bulletin*, January, 1998 and April, 1996.]. The integrity of the cargo tanks was not compromised in either of these two incidents.

In the absence of sufficient historical data, one way of estimating the frequency of occurrence of an event in which LNG would be released from a cargo tank due to damage caused by the ship striking a fixed object (such as the breakwater) is to assume that such an event occurs tomorrow. The assumed frequency of such an event would then be once in 80,000 port calls, or 1.25×10^{-5} per port call.

3.2.3 Release of LNG from Ship's Cargo Tank(s) as a Result of Colliding with Another Ship

A collision between an LNG tank ship and another ship could result in a release of LNG from a cargo tank on the LNG ship, if the momentum (i.e., mass and speed) of the other ship is great enough to cause the failure of the LNG ship's outer hull, inner hull, and cargo tank wall. The resistance of LNG ships to this type of event has been the subject of several studies, as reported in various publications [e.g., Greuner and Böckenhauer, 1980; FERC, 1996; and Eagle Lyon Pope, 2001]. These analyses predicted the minimum speed at which the non-LNG ship would need to be moving at the time of the collision in order to inflict sufficient damage to the LNG tank ship. This critical speed was shown to depend on the momentum of the non-LNG ship; the angle at which that ship strikes the LNG ship; the separation distance between the outer and inner hulls of the LNG ship; and whether the LNG ship is moored or not at the time of the collision.

For a given size and type of non-LNG ship, the critical speed is lowest when that ship is moving in a direction perpendicular to the LNG ship at the time of the collision. As an example, consider a 64,000 dwt bulk carrier or an 82,000 dwt oil tanker striking a membrane tank LNG ship at an angle of 90 degrees. If the LNG tank ship is moored, the critical speed of the striking ship is 3.0 knots [Eagle Lyon Pope, 2001; FERC, 1996].

As discussed in section 3.2.2, there have been about 80,000 chances for an LNG ship to be struck by another ship while in or near a port. Eight such incidents have been reported [Davis, 1979; Thomas and Lakey, 1993; and LNG OneWorld website], but none of these eight incidents resulted in any release of cargo.

Since there is no historical record of a collision in which LNG was released, the method described in sections 3.2.2 and 3.2.3 was used to make an estimate of the frequency of occurrence of an event in which LNG would be released from a cargo tank as a result of a collision between and LNG ship and another ship (i.e., assume that such an event occurs tomorrow. The assumed frequency of such an event would then be once in 80,000 port calls, or 1.25×10^{-5} per port call.

This assumed frequency applies only to collisions that occur outside the POLB breakwater, where there is room to maneuver a large non-LNG ship at a speed of 3 knots or more, or a small ship (3,000 dwt) at a speed of 12.8 knots or more [Eagle Lyon Pope, 2001]. Outside the breakwater, there is a Precautionary Zone (shown in Figure 3-2) in which the speed limit is 12 knots. Ships approaching the POLB must be within the Main Channel, which is outside the breakwater, in order to enter the Outer Harbor. Ships in the Main Channel are restricted to a maximum speed of 10 knots. Inside the breakwater, all ships are restricted to a maximum speed of 6 knots. If an LNG tank ship were to be struck by a small ship (e.g., 3,000 dwt) moving at a speed of 6 knots, the small ship would not have sufficient momentum to penetrate the inner and outer hulls of the LNG tank ship. Thus, once inside the breakwater, a ship collision could result in a spill of LNG only if the non-LNG ship involved in the collision is a large ship, and only if the non-LNG ship is moving in a direction nearly perpendicular to the LNG ship when the collision occurs. The limited dimensions of the port in the area near the proposed terminal would make it very difficult for a large non-LNG ship to make the maneuvers necessary for it to strike the side of an LNG ship while moving at a speed at or above the critical speed. Therefore, this accident is assumed to occur outside the breakwater.

Non-Internet Public

DRAFT ENVIRONMENTAL IMPACT
STATEMENT/ENVIRONMENTAL IMPACT REPORT
FOR THE
LONG BEACH LNG IMPORT PROJECT

Docket No. CP04-58-000, et al.

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Figure 3-2

Public access for the above information is available only through the Public Reference Room, or by e-mail at public.referenceroom@ferc.gov

3.3 Terrorist-Induced Releases of LNG, Natural Gas, or Other Hydrocarbon Fluids in the LNG Terminal

A portion of the qualitative risk analysis of the proposed LNG import terminal in the POLB is centered on estimating the likelihood of a successful terrorist attack on the terminal or shipping operations. Once calculated, this likelihood, or probability can be compared to the probability of the largest worst-case accidental releases.

Unlike events that are accidental in nature, it is impossible to predict the probability of occurrence of specific intentional events (such as those perpetrated by vandals or terrorists). Only the perpetrators of such events know when and where an event will occur. However, within the United States, it is clear that such events are rare or else the historical record of major hazardous events would be skewed as a result of intentional acts. (This has occurred in some countries. For example, in Colombia, the acts of terrorists, rebels, guerrillas, etc., are a major cause of pipeline failures).

There is some indication that flammable fuel facilities in the United States are not an attractive target for sophisticated terrorist attacks. In a March, 2003, United States General Accounting Office report to Congressional Requesters [GAO, 2003], the GAO places focus of potential terrorist attacks on chemical facilities (though it does mention a late-1990s plot to attack a large propane storage facility in California). This can be seen in the following excerpt from the report.

> *Experts agree that chemical facilities present an attractive target for terrorists intent on causing massive damage because many facilities house toxic chemicals that could become airborne and drift to surrounding areas if released. Alternatively, terrorists could steal chemicals, which could be used to create a weapon capable of causing harm. [The Department of] Justice has been warning of the terrorist threat to chemical facilities for a number of years and has concluded that the risk of an attempt in the foreseeable future to cause an industrial chemical release is both real and credible. In fact, according to Justice, domestic terrorists plotted to use a destructive device against a U.S. facility that housed millions of gallons of propane in the late 1990s. In testimony on February 6, 2002, the Director of the Central Intelligence Agency warned of the potential for an attack by al Qaeda on chemical facilities.*
>
> *Some chemical facilities may be at higher risk of a terrorist attack than others when they contain large amounts of toxic chemicals and are located near population centers assuming that the objective is a catastrophic release. Attacks on such facilities could harm a large number of people, with health effects ranging from mild irritation to death, cause large-scale evacuations, and disrupt the local or regional economy. No specific data are available on what the actual effects of successful terrorist attacks on chemical facilities would be. However, facilities subject to the RMP provisions submit to EPA estimates of the potential consequences to surrounding communities of hypothetical accidental "worst-case" chemical releases from their plants. These estimates include the residential population located within the range of a toxic gas cloud produced by a "worst-case"chemical release, called the "vulnerable zone." According to EPA, 123 chemical facilities located throughout the nation have toxic "worst-case" scenarios where more than one million people would be in the "vulnerable zone" and could be at risk of exposure to a cloud of toxic gas. About 600 facilities could each potentially threaten between 100,000 and a million people, and about 2,300 facilities could each potentially threaten between 10,000 and 100,000 people within these facilities' "vulnerable zones."*

A second comment in the report reinforces the conclusion that anti-terrorism activities should be centered on chemical facilities, not flammable facilities.

> *Flammable chemicals affect fewer people because the distance the flammable substance travels tends to be significantly shorter.*

The report goes on to describe the findings of the U.S. Army related to estimating the impacts from chemical releases. Flammable facilities were not included in the Army analysis.

> *The Army has also estimated high potential damage to the population from a toxic chemical release. During a 2001 informal meeting with a number of agencies, the Army Office of the Surgeon General proposed, based on generic estimates, that it was conceivable that as many as 2.4 million people could request medical treatment if a terrorist caused a release of a toxic chemical [U.S. Army, 2001]. According to officials from that office, these estimates include anyone who seeks medical attention as a result of the release—including people with minor irritations or concerns. Finally, a 2002 Brookings Institution report ranks an attack on toxic chemical plants behind only biological and atomic attacks in terms of possible fatalities [Brookings Institution, 2002].* [GAO, 2003]

Experts in consequence and risk assessment would agree with these findings simply based on the ability of a release to inflict injuries. For example, a derailment of a chlorine railcar, accidental or intentional, that resulted in a large leak from a puncture, could result in a toxic vulnerability zone extending approximately three miles from the railcar [Software Program: RMP*Comp]. People inside this vulnerability zone could be exposed to 20 ppm of chlorine for a significant amount of time. 20 ppm of chlorine is the Emergency Response Planning Guideline-3 (ERPG-3) value, which is defined as;

> *The maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening health effects.*

The U.S. EPA uses the ERPG-2 concentration level in its Risk Management Plan (RMP) program. The ERPG-2 concentration level for chlorine is 3 ppm. ERPG-2 is defined as;

> *The maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing or developing irreversible or other serious health effects or symptoms that could impair their abilities to take protective action.*

The chlorine railcar release could create an ERPG-2 vulnerability zone approximately eight miles in radius [Software Program: RMP*Comp].

This example is presented to show that toxic chemicals are a more effective terrorist target than flammable fuel facilities. As will be shown in Section 4, no release from the LNG terminal, accidental or intentional, can produce as large an impact on Long Beach as that from a single railcar of chlorine.

Using the EPA data [GAO, 2003; Belke, 2000], it is possible to define the number of facilities that would have impacts on the surrounding residential population and subdivide these facilities based on the magnitude of the impact following a worst-case event. For instance, for the facilities storing or using toxic chemicals, the following data are available as a result of the EPA Risk Management Plan (RMP).

Table 3-2
EPA RMP Data for Facilities with Toxic Chemicals

Number of U.S. Facilities with Threshold Amounts of Listed Toxic Materials	Affecting this Number of People
123	More than 1,000,000
586	100,000 to 1,000,000
2,306	10,000 to 100,000
4,713	1,000 to 10,000
3,973	100 to 1,000
1,430	10 to 100
855	1 to 10

The following note accompanies the list presented in Table 3-2. This table "includes only those facilities with toxic chemicals that could lead to a "worst-case" scenario. Facilities that only have flammable chemical "worst-case" scenarios are not included. Flammable chemicals affect fewer people because the distance the flammable substance travels tends to be significantly shorter." This statement is borne out by the flammable fuels data reported to the EPA as part of the RMP program [Belke, 2000].

Table 3-3
EPA RMP Data for Facilities with Flammable Chemicals

Number of U.S. Facilities with Threshold Amounts of Listed Flammable Materials	Affecting this Number of People
0	More than 1,000,000
0	100,000 to 1,000,000
40	10,000 to 100,000
250	1,000 to 10,000
720	100 to 1,000
650	10 to 100
1,515	1 to 10

A comparison of Tables 3-2 and 3-3 clearly shows why terrorists might target a facility that stores or uses toxic chemicals in preference to a facility that stores or uses flammable chemicals.

Combining the toxic and flammable fuels facilities into one overall list produces Table 3-4.

Table 3-4
EPA RMP Data for all Facilities

Number of U.S. Facilities with Threshold Amounts of Listed Toxic or Flammable Materials	Affecting this Number of Pe0ple
123	More than 1,000,000
586	100,000 to 1,000,000
2,346	10,000 to 100,000
4,963	1,000 to 10,000
4,693	100 to 1,000
2,080	10 to 100
2,370	1 to 10

Using the EPA's RMP*Comp model [Software Program: RMP*Comp], a worst-case calculation can be made in order to place the proposed LNG terminal in the proper impact category in Tables 3-3 and 3-4. The RMP*Comp program calculates a 0.8 mile vulnerability zone for the proposed LNG terminal. A review of the 2000 US Census data using the program LandView®6 [Software Program: LandView®6] shows there are no residential members of the public within 0.8 miles of the LNG terminal. The Port of Long Beach has estimated that a maximum of 900 workers might be within the 0.8 mile radius circle at any one point in time [S. Crouch, POLB]. Using this data, it is possible to place the proposed LNG terminal in the category that represents the range of 100 to 1000 people within the project's vulnerability zone.

The EPA data base provides a consistent way to review the potential worst-case hazards from over 17,000 facilities in the U.S. For the purposes of this study, only facilities that can produce worst-case impacts in the range of the proposed LNG terminal (100 to 1000 affected people) or greater will be considered. Thus, facilities that have the potential to affect 1 to 10 and 10 to 100 people are removed. This results in 12,711 facilities that have the potential to affect 100 people or more (from 100 to over 1,000,000).

The EPA RMP data provide a numerical accounting of the number of U.S. facilities that might be considered a terrorist target and the potential worst-case impacts following a release from the facilities. The next step in developing a potential "terrorist act" frequency for these facilities is to define a time period of review.

Several high profile terrorist acts have involved U.S. citizens over the past twenty years. A list of such events would include,

June 24, 1985	Highjacking of TWA 847 (Beirut, Lebanon)
October 7, 1985	Highjacking of Achille Lauro (off the coast of Egypt)
December 21, 1988	Bombing of Pan Am 103 (Lockerbie, Scotland)
February 26, 1993	Bombing of World Trade Center (New York, New York)
April 19, 1995	Bombing of Oklahoma City Federal Building (Oklahoma City, Oklahoma)
September 11, 2001	Highjacking of four domestic flights and resultant crashes into the World Trade Center (New York, New York), Pentagon (Arlington, Virginia), and a Pennsylvania field.

From this list, terrorist acts on U.S. soil started no later than February of 1993, with the first bombing of the World Trade Center. It should also be noted that we know of no successful terrorist-initiated act having ever occurred in the facilities covered by Table 3-3 or 3-3. If it is assumed that a successful terrorist event happened tomorrow in any one of the 12,711 facilities, then the frequency of a successful terrorist act could be derived as follows.

$$\frac{1\,event}{11\,years \cdot 12{,}711\ facilities} \text{ or } \frac{1\,event}{139{,}821\ facility\text{-}years}$$

$$= 7.15 \text{ x } 10^{-6}\ \frac{successful\ terrorist\ events}{year}$$

This can be thought of as approximately seven chances in a million per year that a successful terrorist-induced failure would occur in any one of the 12,711 facilities that could have impacts of the same magnitude, or larger than, the impact associated with the proposed LNG import terminal in the Port of Long Beach.

3.4 Security of the LNG Import Terminal

The proposed LNG import terminal will work with local and federal agencies in regard to the physical security of the terminal. For obvious reasons, security plans, actions, and responsibilities will not be described in this report. Those descriptions are not necessary since the potential impacts associated with any intentionally-induced release from the facility is simply defined as possible or impossible. Within the framework of the possible/impossible definition of a successful terrorist event, it has been assumed that it may be possible to overcome all possible layers of security. This does not mean that a terrorist-induced release from the LNG import terminal or shipping activities is likely, credible, or incredible. It simply means that under very specific circumstances, a terrorist-induced release may be possible.

In general, the agencies that would have the most visible local security impact in reference to the LNG terminal operation and LNG tank ship movement security are those listed below.

City of Long Beach

Port of Long Beach

Project security for the import terminal

United States Coast Guard

The majority of the 12,711 facilities referenced in Section 3.3 that have as large or larger potential impacts on the public than the proposed LNG import terminal, have some level of security associated with their operations. The multi-tiered security systems that will be in place in the POLB LNG import terminal exceed the security measures in most of the referenced flammable fuel facilities.

Assuming 7.15 x $(10)^{-6}$ / year is the historical record of a successful terrorist event in a flammable fuel facility as a starting point, it can be argued that the probability of a successful event at the LNG terminal in the POLB is less since there are additional levels of security associated with the terminal that are not present in all the flammable fuels facilities in the data base.

SECTION 4
CONSEQUENCE ANALYSIS

Significant portions of Section 4 describing the calculations made to determine the size and location of possible releases have been removed due to FERC CEII concerns.

4.1 Development of Release Sizes for Accidental Events

For each of the accidental and intentional releases described in Section 2, the final step in developing the information necessary to perform the consequence modeling is the definition of the events that result in a release of LNG, natural gas, or hydrocarbons from the separation plant.

4.1.1 Size of Release Area Following Accidental Failure of Process Equipment

Definitions of the release areas for accidental failures of process equipment are drawn from equipment reviews. For equipment failures, such as pipe ruptures, the highest initial release rate is defined by a full rupture of the associated piping.

4.1.2 Size of Release Area Following Failure of LNG Storage Tanks Due to an Earthquake

Full containment tanks are constructed to standards that preclude some types of failures that might occur in other tank designs. For example, if the inner tank is overfilled, the concrete outer tank will not fail. The concrete outer tank is designed to withstand specific earthquake loads as defined in 49 CFR 193 without loss of product.

As described in Section 3.2.1, an earthquake of a magnitude exceeding the design standards could conceivably cause a failure of the inner tank and outer concrete tank, resulting in a release of LNG. For the purposes of this study, which is to define worst case events, we will assume one or more large cracks develop in the concrete containment wall (as well as the inner tank) with a resultant release area sufficiently large to effect a rapid release of the tank's contents. A large hole in the tank is designed to be representative of an instantaneous catastrophic failure. A catastrophic tank failure scenario is defined as a credible but extremely unlikely event by TNO [TNO, 1999] and the POLB site-specific analysis [KBR, 2005)].

An earthquake of the magnitude necessary to fail a full containment tank would be capable of toppling the security wall surrounding the two LNG tanks. The toppled wall would eventually allow the LNG to overflow the base of the security wall.

4.1.3 Size of Release Area in LNG Tank Ship Following Collision with Breakwater

One possible consequence of an LNG tank ship colliding with the breakwater while entering the Port is a failure of one of the membrane cargo tanks. A second scenario that was evaluated is based on the assumption that the large rate of loss of LNG from one cargo tank compromises the integrity of the inner hull and, over time, leads to sequential releases from the remaining LNG cargo tanks. The failures in the subsequent tanks were assumed to be caused by cracking of portions of the inner hull, followed by tears in the membrane tanks. The initial tank failure was assumed to occur in the cargo tank nearest the bow of the ship (the point of collision with the breakwater). The failures progressed toward the stern of the ship. Each tank was assumed to fail five minutes after the previous tank failure. Thus, for a membrane tank ship with five cargo tanks, this assumption results in all five tanks releasing cargo within 20 minutes of a collision with the breakwater.

4.1.4 Size of Release Area in LNG Tank Ship Following Collision with Another Ship

If an LNG tank ship were to be hit by another ship of sufficient size and speed such that LNG were to be released from one of the membrane tanks [Pitblado, et al., 2004], the sequence of events would be similar to those following a collision of an LNG tank ship with the breakwater.

A second scenario that was evaluated is based on the assumption that the rate of loss of LNG from one cargo tank compromised the integrity of the inner hull and, over time, led to sequential releases from the remaining LNG cargo tanks. The failures in the subsequent tanks were assumed to be caused by cracking of portions of the inner hull, followed by tears in the membrane tanks. The subsequent failures were assumed to occur in five minute intervals. For a membrane tank ship with five cargo tanks, this assumption results in all five tanks releasing cargo within 20 minutes of a collision with another ship.

A summary of the LNG storage tank and LNG tank ship accidental failures is presented in Table 4-1.

Table 4-1
Accidental Releases from LNG Storage Tanks and LNG Tank Ships

Release From
Release from LNG storage tanks following earthquake
Release from LNG tank ship following collision with the breakwater - 1 tank fails
Release from LNG tank ship following collision with the breakwater - 5 tanks fail
Release from LNG tank ship following collision (outside breakwater) with another ship of sufficient size and speed - 1 tank fails
Release from LNG tank ship following collision (outside breakwater) with another ship of sufficient size and speed - 5 tanks fail

4.2 Development of Release Sizes for Intentionally-Induced Events

4.2.1 Size of Release Area Following Intentionally-Induced Failures in Process Equipment

The mechanism defined as that used to cause an intentional failure among the process equipment in the LNG terminal is an explosive charge (e.g., satchel charge). Whether a process pipe or vessel ruptures due to an explosive device or an accidental failure, the release area is assumed to be the same – the area of a ruptured line attached to the vessel.

4.2.2 Size of Release Area Following Commercial Airplane Crash into LNG Storage Tank

Table 2-5 presented a sequence of events that could lead to an intentional crash of a commercial jet airplane into an LNG storage tank. Table 4-2 defines the sequence of events that could result in a release of LNG from the full containment storage tanks following the plane's impact.

Table 4-2
Terrorist-Hijacked Airplane Crashing Into One or Both LNG Tanks

Consequence	Notes
Jet engine hits tank wall at near perpendicular angle.	All supporting calculations, documentation, and references in regard to calculating the size and location of potential release area(s) for this scenario have been removed due to FERC CEII concerns.
Engine penetrates LNG storage tank concrete shell.	
Engine penetrates LNG storage tank insulation and inner nickel steel tank.	
LNG will be released from a hole in the inner (nickel steel) and outer (concrete) shell.	
Vapors evolving off LNG will immediately be ignited.	
LNG will spread over the area surrounding the LNG tanks.	
LNG will escape the area enclosed by the security wall.	
LNG flows over land and onto the water surface.	

4.2.3 Release From an LNG Storage Tank Following a Truck Bomb

Table 2-6 presented a sequence of events that could lead to an explosion of a truck bomb beside an LNG storage tank. Table 4-3 defines the sequence of events that could result in a release of LNG from a full containment storage tank following detonation of a truck bomb.

Table 4-3
Terrorist Detonates Truck Bomb Near an LNG Tank

Consequence	Notes
Explosives detonate, resulting in hole in LNG tank and surrounding security wall.	All supporting calculations, documentation, and references in regard to calculating the size and location of potential release area(s) for this scenario have been removed due to FERC CEII concerns.
LNG will be released from the storage tank.	
Vapors evolving off LNG will immediately be ignited.	
LNG will spread over the area surrounding the LNG tanks.	
LNG will escape the area enclosed by the security wall.	
LNG flows over land and onto the water surface.	

4.2.4 Release From an LNG Storage Tank Following the Impact of a Rocket-propelled Grenade

Table 2-7 presented a sequence of events that could lead to one of the LNG storage tanks being hit by an RPG. Table 4-4 defines the sequence of events that could result in a release of LNG from a full containment storage tank following the impact of an RPG.

Table 4-4
Terrorist Fires Rocket-propelled Grenade (RPG) Into One or Both LNG Tanks

Consequence	Notes
RPG hits tank at near perpendicular angle.	All supporting calculations, documentation, and references in regard to calculating the size and location of potential release area(s) for this scenario have been removed due to FERC CEII concerns.
RPG warhead penetrates storage tank.	
LNG will be released from a single hole.	

4.2.5 Release From LNG Tank Ship Following Crash of Commercial Airplane

Table 2-9 presented a sequence of events that could lead to an intentional crash of a commercial jet airplane into an LNG tank ship docked at the terminal. Table 4-5 defines the sequence of events that could result in a release of LNG from the LNG tank ship following the plane's impact.

Table 4-5
Terrorist-Hijacked Airplane Crashing Into an LNG Tank Ship

Consequence	Notes
Jet aircraft hits tank ship.	All supporting calculations, documentation, and references in regard to calculating the size and location of potential release area(s) for this scenario have been removed due to FERC CEII concerns.
Engine penetrates LNG tank ship outer and inner hulls.	
Engine penetrates LNG insulation and membrane cargo tank.	
LNG will be released from holes in two adjacent membrane cargo tanks.	
Vapors evolving off LNG will immediately be ignited.	
LNG flows out of the cargo tanks and onto the water surface.	

4.2.6 Release From an LNG Tank Ship Following a Boat Bomb

Table 2-10 presented a sequence of events that could lead to an explosion of a boat bomb beside an LNG tank ship docked at the terminal. Table 4-6 defines the sequence of events that could result in a release of LNG from the tank ship following detonation of a boat bomb.

Table 4-6
Terrorists Place Boat Bomb Beside an LNG Tank Ship

Consequence	Notes
Explosives detonate, resulting in hole in LNG tank ship outer hull, inner hull, insulation, and LNG membrane tank.	All supporting calculations, documentation, and references in regard to calculating the size and location of potential release area(s) for this scenario have been removed due to FERC CEII concerns.
LNG will be released from a membrane cargo tank.	
Vapors evolving off LNG will immediately be ignited.	
LNG will spread over the water surface beside the LNG tank ship.	

4.2.7 Release From an LNG Tank Ship Following the Impact of a Rocket-propelled Grenade

Table 2-11 presented a sequence of events that could lead to a LNG tank ship being hit by an RPG while docked at the terminal. Table 4-7 defines the sequence of events that could result in a release of LNG from an LNG tank ship following the impact of an RPG.

Table 4-7
Terrorist Fires Rocket-propelled Grenade (RPG) Into LNG Tank Ship

Consequence	Notes
RPG hits tank ship at near perpendicular angle and penetrates outer and inner hull.	All supporting calculations, documentation, and references in regard to calculating the size and location of potential release area(s) for this scenario have been removed due to FERC CEII concerns.
RPG warhead penetrates storage tank.	
LNG will be released from a single hole.	

4.2.8 Release From an LNG Tank Ship Following a Collision with Another Ship

Table 2-12 presented a sequence of events that could lead to an LNG tank ship being involved in an intentional collision with another ship. Table 4-8 defines the sequence of events that could result in a release of

LNG from an LNG tank ship following a collision with another ship. Note that the release from this event would be identical to that which would occur if the collision was accidental in nature.

Table 4-8
Terrorist-Controlled Ship Collides with an LNG Tank Ship

Consequence	Notes
Collision results in puncture of one LNG cargo tank.	All supporting calculations, documentation, and references in regard to calculating the size and location of potential release area(s) for this scenario have been removed due to FERC CEII concerns.
LNG flows out of one cargo tank and onto the water surface.	
Loss of LNG from one cargo tank leads to failures of other cargo tanks.	
LNG flows out of all cargo tanks and onto the water surface.	

4.2.9 Summary of Release Sizes Due to Intentional Events

A summary of the releases from LNG storage tanks and LNG tank ships due to intentional events is presented in Table 4-9

Table 4-9
Intentionally Caused Releases
from LNG Storage Tanks and LNG Tank Ships

Release From
Release from LNG storage tank after plane crash
Release from LNG storage tank after truck bomb
Release from LNG storage tank after RPG
Release from LNG tank ship after plane crash - 2 tanks fail
Release from LNG tank ship after plane crash - 5 tanks fail
Release from LNG tank ship after boat bomb - 1 tank fails
Release from LNG tank ship after boat bomb - 5 tanks fail
Release from LNG tank ship after RPG
Release from LNG tank ship afer collision with another ship - 1 tank fails
Release from LNG tank ship afer collision with another ship - 5 tanks fail

4.3 Consequence Analysis Models

Each selected release scenario was evaluated to determine the extent and location of a hazard, or hazards, associated with the release. When performing site-specific consequence analysis studies, the ability to accurately model the phenomena associated with a particular hazard is important if an accurate assessment of the potential exposure is to be attained. For this study, one or more models were used to quantify the hazard, or hazards, of each release. All models have built-in assumptions and limitations. The models used in this study are briefly described below, along with their restrictions for use.

4.3.1 FERC Model for LNG Spills onto Water

In the report titled *Consequence Assessment Methods for Incidents Involving Releases from Liquefied Natural Gas Carriers* [FERC, 2004], FERC presents a coupled set of models to determine the release and spread of LNG onto a water surface. The spreading LNG can be assumed to be ignited, or unignited, during the release. If ignited, a solid flame pool fire model defines the radiant impact zone. If unignited, the model produces a time-varying vaporization profile appropriate for input into the DEGADIS dispersion model. The FERC model was developed for use under the following conditions.

- Releases from LNG tank ships
- Releases from a single source of LNG
- Releases onto quiescent water
- Releases onto water without obstructions (e.g., docks, quays, or shoreline)

The model has limitations and cannot be used for the following;

- Releases onto any surface other than a large open body of water
- Releases from an elevation above water level
- Releases of pressurized LNG
- Releases onto rough or non-quiescent water
- Releases into bounded or obstructed areas (e.g., water surfaces bounded by docks)
- Releases of materials other than LNG

4.3.2 DEGADIS

The DEGADIS [GRI, 1990a] suite of models was developed to simulate the dispersion of denser-than-air vapor clouds. DEGADIS is cited in 49 CFR 193 as one of the models appropriate for use in evaluating the flammable cloud dispersion distances following a spill of LNG. It is appropriate to use the DEGADIS models for some, but not all, of the vapor dispersion calculations required in this work. There are two primary sub-models in the DEGADIS suite of models; one for clouds evolving from a liquid pool, and one for vertical momentum jets of vapor. The models were developed for use under the following conditions.

- Vapors evolving from a pool of LNG on water or land
- Vertical releases of gases (e.g., discharge from a relief valve)

The DEGADIS dispersion models have limitations and cannot be used to actually model the following;

- Releases of pressurized or superheated liquids
- Releases of pressurized gases at any angle other than vertical

The DEGADIS suite of models does not calculate a release rate, liquid spreading rate, or associated transient vaporization rate. This information must be supplied by one or more outside models.

4.3.3 LNGFIRE3

The LNGFIRE3 model developed by GRI [GRI, 1990b] is a pool fire model developed to predict the thermal radiation hazards present when the vapors emanating from a pool of LNG are ignited. The model is recommended for use in 49 CFR 193, and is capable of simulating circular and rectangular pools, as well as trenches carrying LNG. There is limited capability for modifying the properties of LNG used in the model. LNGFIRE3 was developed for the following specific conditions.

- Pool fires over fixed-sized pools of LNG
- Pool fires on land

LNGFIRE3 cannot be used for the following;

- LNG pool fires on water
- Pool fires for materials other than LNG
- Jet/torch fires

In addition, LNGFIRE3 does not calculate the spreading or size of an unconfined LNG pool. This information must be supplied to the model.

4.3.4 CANARY by Quest

CANARY by Quest contains a set of complex models that calculate multicomponent thermodynamic properties, release rates and phases, initial dilution of the vapor (dependent upon the release characteristics), and the subsequent dispersion of the vapor introduced into the atmosphere. The models contain algorithms that account for thermodynamics, mixture behavior, transient release rates, gas cloud density relative to air, initial velocity of the released gas, and heat transfer effects from the surrounding atmosphere and the substrate.

CANARY also contains models for pool fire and torch fire radiation. These models account for impoundment configuration, material composition, target height relative to the flame, target distance from the flame, atmospheric attenuation (includes humidity), wind speed, and atmospheric temperature.

For vapor cloud overpressure calculations, CANARY employs the Baker-Strehlow method. It accounts for the reactivity of the fuel in the vapor cloud, the size of the flammable vapor cloud, and the degree to which the vapor cloud is obstructed or confined. The model is based on experimental and historical observations of vapor cloud explosions and deflagrations, with relation to the amount of confinement and obstruction present in the volume occupied by the vapor cloud.

All of the hazard models in CANARY are based on information in the public domain (published literature) and have been validated with experimental data. Technical descriptions of the CANARY models used in this study are presented in Appendix B.

4.3.5 Application of Consequence Models

All accidental and intentional releases were evaluated with one or more of the models listed above. In rare instances, when no model was capable of evaluating a phenomenon (e.g., sequential leakage from multiple tanks), additional calculations were made. In other instances, a model was modified slightly in order to accept an input it could handle, but was not designed for. An example of this was the modification of the FERC model to accept a time-varying, non-monotonically-decreasing mass release rate. This modification was necessary in order to use the FERC spreading model for the multi-tank LNG ship failure scenarios.

A list of the release scenarios identified in this analysis is given in Table 4-10. For each release identified, several potential hazardous outcomes might be possible. The models employed for each calculation are identified in Table 4-10.

4.4 Release Rate Calculations

The FERC and CANARY models have the ability to calculate the transient rate of release of a fluid. The FERC model is limited in that it can only be used for LNG releases from static atmospheric pressure tanks. Thus, the FERC model cannot be used for any of the process area releases since they are non-static systems and are under pressure. As shown in Table 4-10, the FERC model (or a slight variation thereof) was used only for LNG releases from the tank ships.

Table 4-10
Consequence Models Used in Analysis
Facility = LNG Import Terminal at Port of Long Beach, California

Cause of Release (A) = Accidental (I) = Intentional	Thermo-dynamics	Release Rate	Liquid Spreading and Vaporization	Vapor Dispersion From a Pool	Vapor Dispersion From a Jet	Vapor Cloud Explosion	Pool Fire	Torch Fire
(A) (I) Rupture of process equipment - location A *	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY
(A) (I) Rupture of process equipment - location B *	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY
(A) (I) Rupture of process equipment - location C *	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY
(A) (I) Rupture of process equipment - location D *	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY
(A) (I) Rupture of process equipment - location E *	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY
(A) (I) Release from process equipment - location F *	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY
(A) (I) Release from process equipment - location G *	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY
(A) Release from LNG storage tanks following earthquake	CANARY	CANARY	CANARY FERC(1)	DEGADIS		CANARY	LNGFIRE3 FERC(1)	
(A) (I) Release from LNG tank ship following collision (outside breakwater) - 1 tank fails		FERC	FERC	DEGADIS			FERC	

FERC(1) = FERC model modified to accept external transient release rate data
FERC(2) = FERC model modified to combine transient outflow from multiple sources
* = Details have been removed because this is considered to be Critical Energy Infrastructure Information (CEII) by the FERC

Table 4-10
Consequence Models Used in Analysis
Facility = LNG Import Terminal at Port of Long Beach, California
(Continued)

Cause of Release (A) = Accidental (I) = Intentional		Thermo-dynamics	Release Rate	Liquid Spreading and Vaporization	Vapor Dispersion From a Pool	Vapor Dispersion From a Jet	Vapor Cloud Explosion	Pool Fire	Torch Fire
(A) (I)	Release from LNG tank ship following collision (outside breakwater) - 5 tanks fail	CANARY	FERC(2)	FERC(1)	DEGADIS		CANARY	FERC(1)	
(I)	Release from LNG storage tank after plane crash	CANARY	CANARY	CANARY FERC(1)				LNGFIRE3 FERC(1)	
(I)	Release from LNG storage tank after truck bomb	CANARY	CANARY	CANARY FERC(1)				LNGFIRE3 FERC(1)	
(I)	Release from LNG storage tank after RPG	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY	CANARY
(I)	Release from LNG tank ship after plane crash - 2 tanks fail		FERC(2)	FERC(1)				FERC(1)	
(I)	Release from LNG tank ship after plane crash - 5 tanks fail		FERC(2)	FERC(1)				FERC(1)	
(I)	Release from LNG tank ship after boat bomb - 1 tank fails		FERC	FERC				FERC(1)	
(I)	Release from LNG tank ship after boat bomb - 5 tanks fail		FERC(2)	FERC(1)				FERC(1)	
(I)	Release from LNG tank ship after RPG	CANARY	FERC	FERC	CANARY	CANARY	CANARY	CANARY	CANARY

FERC(1) = FERC model modified to accept external transient release rate data
FERC(2) = FERC model modified to combine transient outflow from multiple sources

4.4.1 Release Rate Calculations for Process Equipment Releases

An example of the transient release rate from output provided by the CANARY model is presented in Figure 4-1. The release is caused by the rupture of process equipment F. As can be seen in Figure 4-1, the fluid (released under 580 psig pressure) forms an aerosol composed of vapor and suspended liquid droplets. Virtually none of the liquid reaches the ground. The mass rate of release decays until the inventory is exhausted (about 30 seconds). This aerosol flow rate is input to the torch fire radiation model or the momentum jet dispersion model, dependent on the hazard being evaluated.

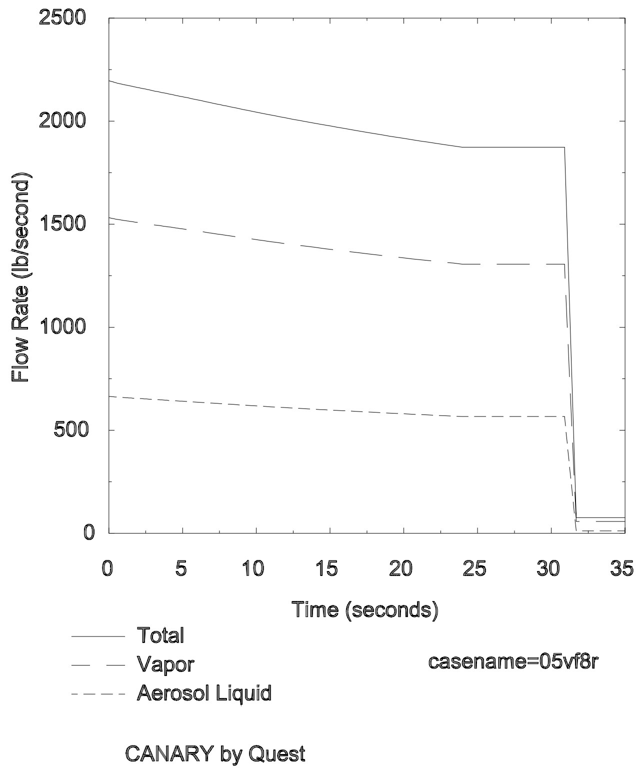

Figure 4-1
Release Rate from Process Equipment F

Calculations for all the process equipment failures (accidental or intentional) were made in a similar manner using the CANARY model.

4.4.2 Release Rate Calculations for Storage Tank Failures Due to an Earthquake

The maximum inventory in the LNG storage tanks would occur just after an LNG tank ship finishes unloading its cargo. This is represented by one full (160,000 m^3) tank and one half-full tank. (One tank is assumed to be only half full since LNG would be withdrawn from this tank while the other tank is being filled.) The release rate calculations were performed with CANARY. The release rate from the full tank is presented in Figure 4-2 and the release rate from the half-full tank is presented in Figure 4-3.

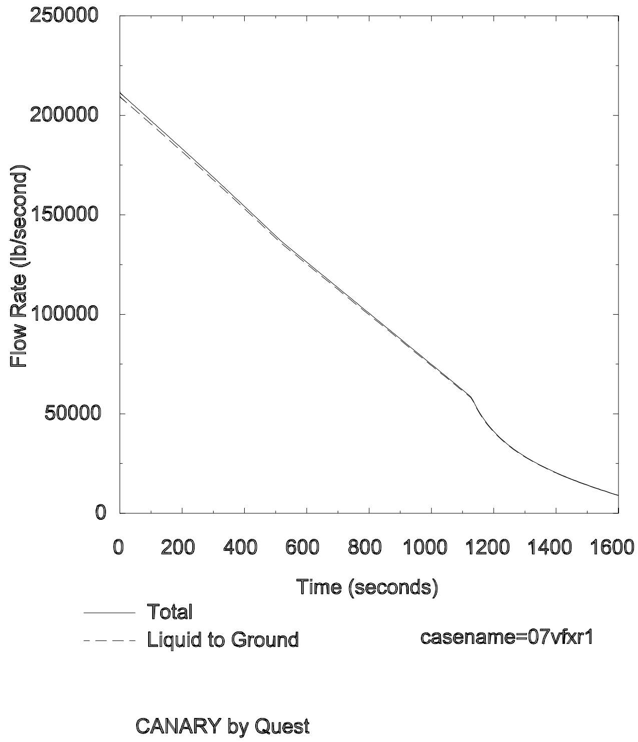

Figure 4-2
Release Rate from Failure of Full LNG Storage Tank Following an Earthquake

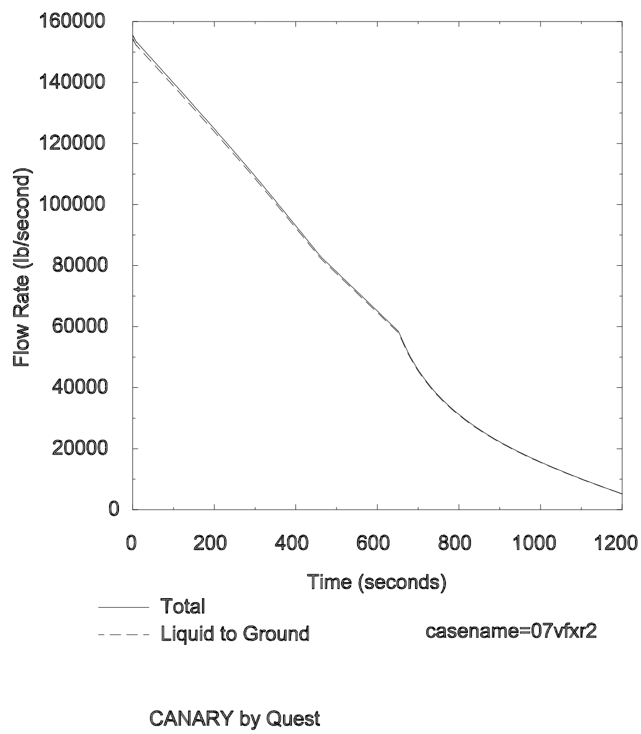

Figure 4-3
Release Rate from Failure of a Half-Full LNG Storage Tank Following an Earthquake

4.4.3 Release Rate Calculations from an LNG Tank Ship Following Collision with the Breakwater

As described in Section 4.1.3, a collision of an inbound LNG tank ship with the breakwater could release LNG from one membrane tank or result in the sequential failure of all five membrane tanks. The release rate results for the single tank failure were made with the FERC model and are presented in Figure 4-4. The FERC model was modified to accept multiple release sources, such as that required for the sequential tank failure scenario. The release rate results for the sequential tank failure scenario are also presented in Figure 4-4.

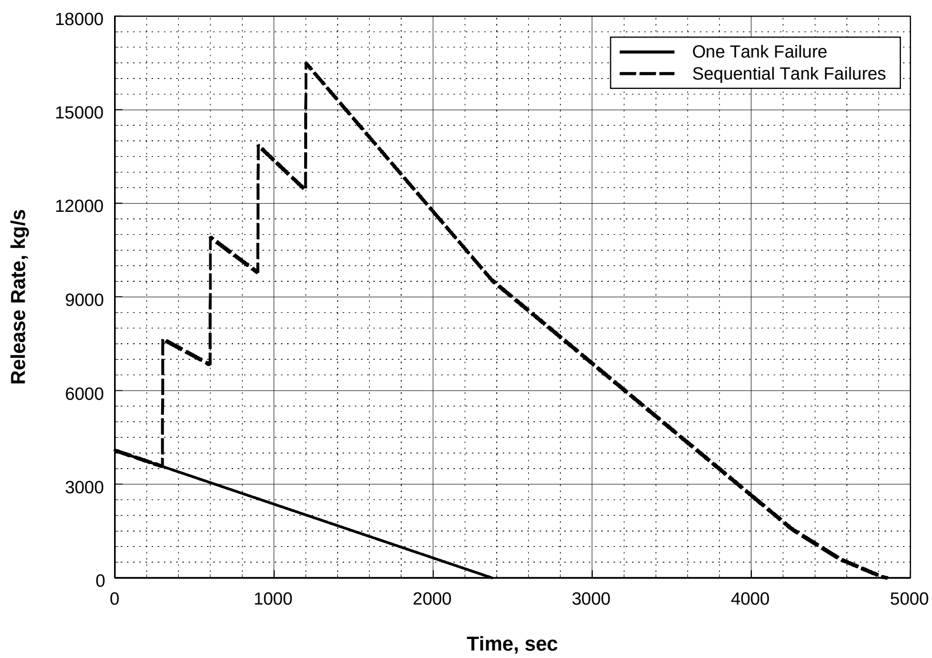

Figure 4-4
Release Rate from Failure of One Membrane Tank
and from Sequential Failure of Five Membrane Tanks
on an LNG Tank Ship Following Collision with the Breakwater

4.4.4 Release Rates Summary

These three scenarios (pressurized process area release, LNG storage tank release, and LNG tank ship release) cover the range of fluid releases from aerosol jets (no liquid to the ground), to single point (one tank) failures, to sequential failures of multiple tanks. The three accidental scenarios presented were run under non-fire conditions. This condition maximizes the LNG liquid pool diameter (when applicable).

These three scenarios represent the range of release rate calculations made for both the accidental and intentional releases.

4.5 Liquid Spreading and Vaporization Calculations

4.5.1 Liquid Spreading Calculations for Process Equipment Releases

Many of the process area releases result in high velocity, flashing fluid aerosol jets that produce very little liquid on the ground. In these cases, the inputs to the fire radiation and vapor dispersion models are dominated by the momentum jet. An example of this was provided in Section 4.4.1 for the release from process equipment F.

4.5.2 Liquid Spreading Calculations for Storage Tank Failures Due to an Earthquake

For the cases where LNG is released onto the ground inside the security fence surrounding the LNG storage tanks, the CANARY model calculates the spreading and vaporization of the liquid on land. As an example, for the case where an earthquake causes the storage tanks to fail, the vaporization history of the LNG spilled on the land surface is presented in Figure 4-5.

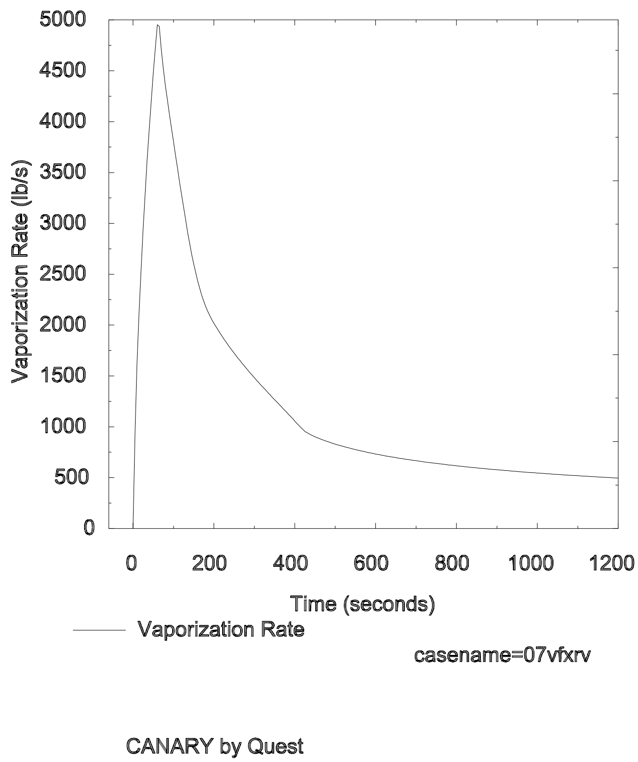

Figure 4-5
LNG Vaporization Rate for Land-Based Pool
Following Tank Failure Due to an Earthquake

In the earthquake case, the bulk of the LNG released from the storage tanks ends up flowing through the collapsed security wall and out onto the water surrounding the facility. Modifying the FERC spreading and vaporization program to accept the LNG outflow released from the two storage tanks and overflowing the security wall and onto the surrounding water results in the transient vaporization profile presented in Figure 4-6. The FERC model predicts the maximum radius of the semicircle formed by the LNG on water to be 2,700 feet (non-burning case).

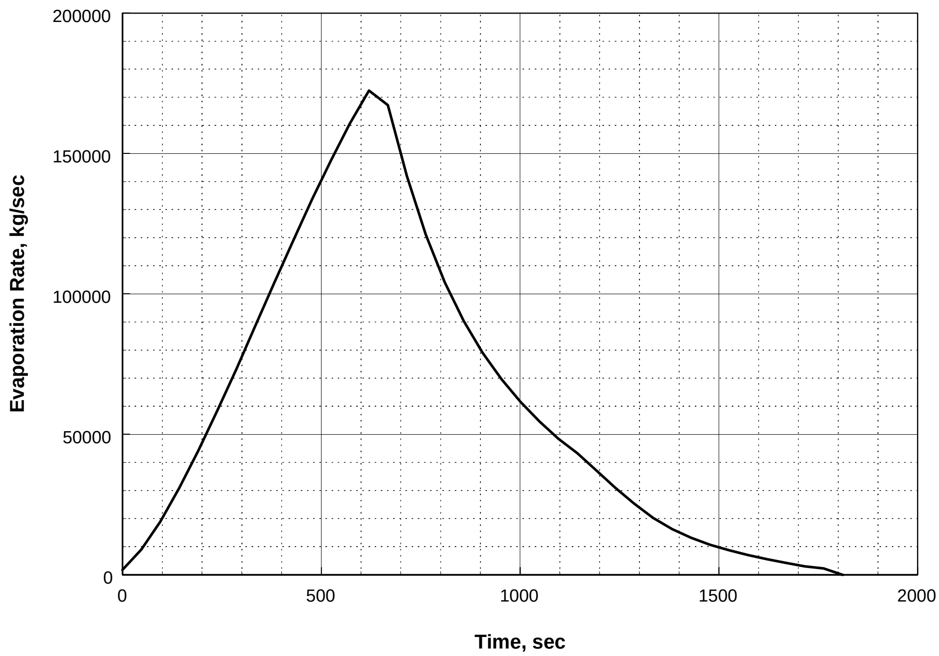

Figure 4-6
Vaporization Rate History from LNG Reaching Water Surface Following Failure of LNG Storage Tanks After an Earthquake (Modified FERC Model - Non-Burning Case)

4.5.3 Liquid Spreading Calculations from LNG Tank Ship Following Collision with the Breakwater

As described in Section 4.1.3, the collision of an inbound LNG tank ship with the breakwater could release LNG from one membrane tank or result in the sequential failure of all five membrane tanks. The FERC model was modified to accept multiple release sources so it could be used to model the sequential tank failure scenario. The transient vaporization results for both the single tank failure and sequential tank failure scenarios are presented in Figure 4-7. These spreading results are for the case where the LNG pool is not on fire. The maximum radius of the FERC-defined semicircle is 450 ft for the single tank failure and 820 ft for the multiple tank failure.

Similar release rate, pool spreading, and vaporization history calculations were made for all accidental and intentional release cases listed in Tables 4-2 through 4-8. Table 4-10 identifies the model used (CANARY, FERC, or modified FERC) for each calculation.

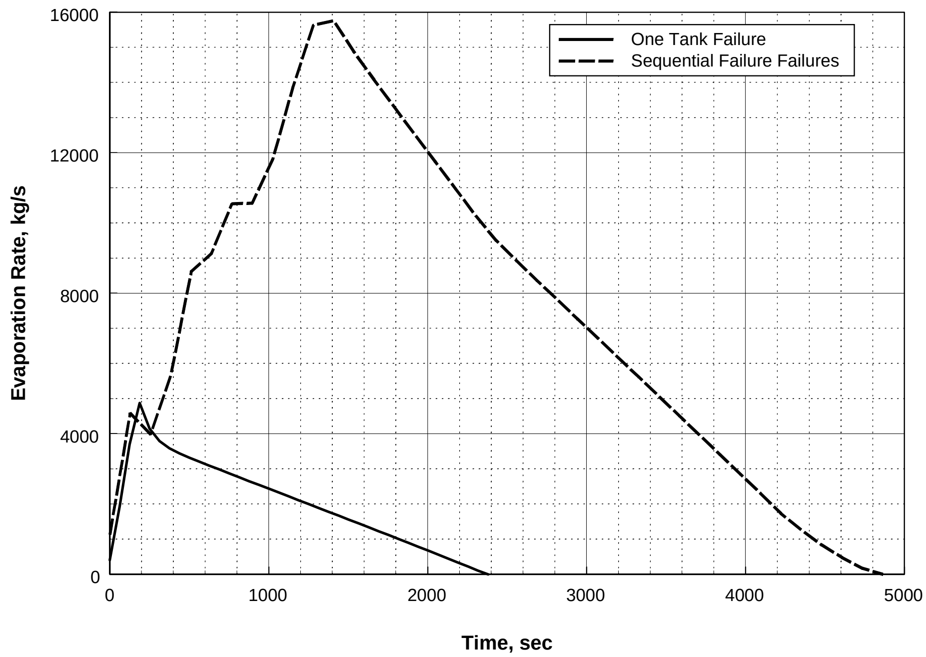

Figure 4-7
Vaporization Rate History from Failure of One Full Membrane Tank and from Sequential Failure of Five Full Membrane Tanks on an LNG Storage Tank Ship Following Collision with the Breakwater
(Modified FERC Model - Non-Burning Case)

4.6 Fire Radiation Calculations

In each accidental and intentional release identified, there is a possibility that the vapor released (either directly, such as a natural gas release, or indirectly, such as vapors evolving off a liquid pool) will be ignited. The ignition source may be accidental in nature or intentional (as in the case of explosive devices). The resultant fire may be in the form of jet fire, pool fire, or both, dependent on the nature of the release.

4.6.1 Hazard Footprints and Vulnerability Zones

When conducting consequence analysis calculations, it may be necessary to determine the impact of each possible combination of:

- hole size,
- release orientation,
- release outcome,
- atmospheric stability,
- wind speed, and
- wind direction

for each potential release included in the study. For each potential release, each unique combination of these factors results in a "unique accident." In this study, the focus is on determining the worst-case impacts. Thus, the hole size, release orientation, wind speed, and atmospheric stability have been defined. What is not known is the wind direction. Depending on which way the wind is blowing, a different area around the release point (or the point defined as the center of the hazard) may be exposed to a hazardous condition. It is important to distinguish between the largest area potentially exposed to a radiant impact from a single accident and the total area that could be exposed to any possible radiant impact from a single accident.

A hazard footprint can be defined as the area over which a given unique accident is capable of producing some level of undesirable consequences (e.g., radiant flux of at least 1,600 Btu/(hr$\cdot$ft^2)). A vulnerability zone is defined as the area within the circle created by rotating a hazard footprint around its point of origin. Any point within that circle could, under some set of circumstances, be exposed to a hazard level that equals or exceeds the endpoint used to define the hazard footprint. However, except for accidents that produce circular hazard zones (e.g., Boiling Liquid Expanding Vapor Explosions (BLEVEs)), only a portion of the area within the vulnerability zone can be affected by a unique accident. This is illustrated in Figure 4-8 by the 1,600 Btu/(hr$\cdot$ft^2) radiant flux footprint generated by immediate ignition of the flashing fluid release from process equipment F. The hazard footprint (cross-hatched area) and its vulnerability zone (the circle) are both presented.

Vulnerability zones can be used to define the size and shape of the area around a release within which there is a finite probability of exposure to the defined hazard level. Persons located outside this area would not be at risk to the hazard level defined. Thus, for the process equipment F, persons outside the vulnerability zone presented in Figure 4-8 would not be affected by a 1,600 Btu/(hr$\cdot$ft^2) radiant hazard under any condition.

The 1,600 Btu/(hr$\cdot$ft^2) vulnerability zone presented in Figure 4-8 for the process equipment F fire scenario was generated with the CANARY software. The generation of a hazard footprint requires three-dimensional radiant flux maps be calculated. The LNGFIRE3 and FERC fire models do not calculate the radiant flux data to this level of detail. Thus, when the LNGFIRE3 and FERC radiation models are used, only the vulnerability zone (a circle) can be calculated. Used incorrectly, this information can lead to an overestimation of the possible radiant impact of a fire.

4.6.2 Fire Radiation Calculations for Storage Tank Failures Due to an Earthquake

As described in Section 4.1.2, an earthquake of a magnitude sufficient to cause a failure of one or both of the LNG storage tanks would also cause the failure of the security wall. With the failure of the security wall, there is the potential to have a pool of LNG on shore, generally confined by the remnants of the security wall, and as an expanding pool on the water surface. It is almost certain that an earthquake of the magnitude necessary to fail one or both LNG storage tanks would also create multiple ignition sources in the immediate area, thus igniting the natural gas/air mixture formed during the release.

In order to model this scenario, two individual calculations were run. The first employed LNGFIRE3 to calculate the 1,600 Btu/(hr$\cdot$ft^2) radiant impact zone due to the land-based pool fire. The second employed the FERC model to calculate the water-based pool fire. The 1,600 Btu/(hr$\cdot$ft^2) vulnerability zone from the LNGFIRE3 model is presented in Figure 4-9 (the smaller circle). The 1,600 Btu/(hr$\cdot$ft^2) vulnerability zone from the FERC model is also presented in Figure 4-9 (the larger circle).

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Figure 4-9

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A comparison of the two vulnerability zones shows that the water-based fire clearly defines the size of the vulnerability zone. Even if the wind is blowing from the east-southeast (from the water toward the storage tank area) the extent of the vulnerability zone created by the water-based pool fire dominates the result and serves to define the 1,600 Btu/(hr$\cdot$ft^2) vulnerability zone for this scenario.

4.6.3 Fire Radiation Calculations for an LNG Tank Ship Collision with the Breakwater

The water-based pool fire calculations for the scenarios in which the LNG tank ship collides with the breakwater were made with the FERC model. The scenario that involves one tank failure is directly modeled with the FERC pool fire model. The 1,600 Btu/(hr$\cdot$ft^2) vulnerability zone calculated by the FERC model is presented in Figure 4-10. The sequential tank failure scenario requires modification of the FERC model to accept a transient, non-monotonically-decreasing liquid outflow. With this modification, the FERC model calculates the 1,600 Btu/(hr$\cdot$ft^2) vulnerability zone for the five tank sequential failure and is presented in Figure 4-11.

Although immediate ignition of the evolving natural gas vapors from the spilled LNG is less likely in this scenario than in the LNG storage tank failures due to an earthquake, the ignition of the spill results in the worst case pool fire impacts.

4.6.4 Summary of Fire Radiation Calculations

Fire radiation calculations were made using the models defined in Table 4-10 for each accidental and intentional release scenario. Maximum distances to the 1,600 Btu/(hr$\cdot$ft^2) radiant hazard endpoint are presented in Table 4-11. Since several of the potential releases involve LNG pools that may move away from the release point before they are ignited, or while they are ignited, the center of each fire is also identified in Table 4-11. When defining the extent of the 1,600 Btu/(hr$\cdot$ft^2) vulnerability zone for each release, the center of the fire should be used as the reference point.

Plots of the 1,600 Btu/(hr$\cdot$ft^2) vulnerability zones for several of the scenarios are presented in Figures 4-12 through 4-17. These plots are listed in Table 4-11.

4.7 <u>Flammable Vapor Cloud Dispersion Calculations</u>

The ability of a release of LNG, natural gas, or other hydrocarbons to develop into a drifting cloud is dependent on the mechanism that caused the release. When analyzing the possible progression of events following accidental failures (see Section 3.1.1), there are often four possible outcomes.

- Immediate ignition followed by a fire (pool or torch)
- Delayed ignition producing a flash fire (and possible pool or torch fire)
- Delayed ignition producing a flash fire and some amount of overpressure
- No ignition; dissipation of hydrocarbon vapors below flammable limits

As described in Section 3, the probability of each outcome is dependent on a number of factors. In many cases, the probability of immediate ignition of an accidental release is not 100%. Thus, there is a possibility of the formation of a drifting cloud of flammable gas followed by the eventual ignition of the cloud that creates a flash fire. In some instances, the flash fire may lead to overpressures above some minimal level.

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Figure 4-10

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Figure 4-11

Table 4-11
Consequence Analysis Results
Facility = LNG Import Terminal at Port of Long Beach, California

Cause of Release (A) = Accidental (I) = Intentional		Distance (ft) to 1,600 Btu/(hr·ft^2) Radiant Flux Level	Measured From	Figure	Distance (ft) to 1 psig Overpressure	Distance (ft) to LFL
(A) (I)	Rupture of process equipment - location A*	280	Release Point	—	NA	1,705
(A) (I)	Rupture of process equipment - location B*	270	Release Point	—	320	585
(A) (I)	Rupture of process equipment - location C*	530	Release Point	—	190	995
(A) (I)	Rupture of process equipment - location D*	240	Release Point	—	190	545
(A) (I)	Rupture of process equipment - location E*	490	Release Point	—	NA	400
(A) (I)	Release from process equipment - location F*	830	Release Point	Figure 4-8	320	990
(A) (I)	Release from process equipment - location G*	360	Release Point	—	320	700
(A)	Release from LNG storage tanks following earthquake	8,610	Center of LNG Pool on Water	Figure 4-9	NA	36,400
(A)	Release from LNG tank ship following collision with breakwater - 1 tank fails	2,200	Center of LNG Pool by Tank Ship	Figure 4-10	NA	9,260
(A)	Release from LNG tank ship following collision with breakwater - 5 tanks fail	3,345	Center of LNG Pool by Tank Ship	Figure 4-11	NA	19,330

NA = Explosion overpressure level not achieved
DNA = Does not apply – vapor cloud formation is not possible following initiating event
* = Details have been removed because this is considered to be Critical Energy Infrastructure Information (CEII) by the FERC

Table 4-11
Consequence Analysis Results
Facility = LNG Import Terminal at Port of Long Beach, California
(Continued)

Cause of Release (A) = Accidental (I) = Intentional		Distance (ft) to 1,600 Btu/(hr•ft^2) Radiant Flux Level	Measured From	Figure	Distance (ft) to 1 psig Overpressure	Distance (ft) to LFL
(A) (I)	Release from LNG tank ship following collision (outside breakwater) - 1 tank fails	2,980	Center of LNG Pool on Water	—	NA	16,510
(A) (I)	Release from LNG tank ship following collision (outside breakwater) - 5 tanks fail	3,370	Center of LNG Pool on Water	—	NA	21,200
(I)	Release from LNG storage tank after plane crash	2,835	Center of LNG Pool on Water	Figure 4-12	DNA	DNA
(I)	Release from LNG storage tank after truck bomb	7,020	Center of LNG Pool on Water	Figure 4-13	DNA	DNA
(I)	Release from LNG storage tank after RPG	230	LNG Pool by Tank	—	NA	130
(I)	Release from LNG tank ship after plane crash - 2 tanks fail	3,635	Center of LNG Pool by Tank Ship	Figure 4-14	DNA	DNA
(I)	Release from LNG tank ship after plane crash - 5 tanks fail	3,635	Center of LNG Pool by Tank Ship	Figure 4-15	DNA	DNA
(I)	Release from LNG tank ship after boat bomb - 1 tank fails	3,115	Center of LNG Pool by Tank Ship	Figure 4-16	DNA	DNA
(I)	Release from LNG tank ship after boat bomb - 5 tanks fail	3,320	Center of LNG Pool by Tank Ship	Figure 4-17	DNA	DNA
(I)	Release from LNG tank ship after RPG	115	Center of LNG Pool by Tank Ship	—		460

NA = Explosion overpressure level not achieved
DNA = Does not apply – vapor cloud formation is not possible following initiating event

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Figure 4-12

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Figure 4-13

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Figure 4-14

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Figure 4-15

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Figure 4-16

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Figure 4-17

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When considering intentional releases, the device that is used to effect the release of LNG, natural gas, or other hydrocarbons often involves an explosive or is itself a significant ignition source. In many of these cases, there is no opportunity for an evolving vapor/air flammable mixture to avoid the immediate and sustained ignition source. Thus, these releases will follow the immediate ignition path and result in a pool fire, torch fire, or both.

Table 4-12 presents a summary of the accidental and intentional events that have the potential to develop a flammable cloud following a release of LNG, natural gas, or other hydrocarbons. These cases require dispersion calculations to determine the maximum extent of a drifting flammable cloud under worst case conditions.

Table 4-12
Ability of Release Events to Allow Vapor Cloud Development

Release	Development of Flammable Cloud Following Accidental Release?	Development of Flammable Cloud Following Intentional Release?
Rupture of process equipment - location A*	Yes	No
Rupture of process equipment - location B*	Yes	No
Rupture of process equipment - location C*	Yes	No
Rupture of process equipment - location D*	Yes	No
Rupture of process equipment - location E*	Yes	No
Release from process equipment - location F*	Yes	No
Release from process equipment - location G*	Yes	No
Release from LNG storage tanks following earthquake	Yes	NA
Release from LNG tank ship following collision with the breakwater - 1 tank fails	Yes	Yes
Release from LNG tank ship following collision with the breakwater - 5 tanks fails	Yes	Yes
Release from LNG tank ship following collision (outside breakwater) with another ship of sufficient size and speed - 1 tank fails	Yes	Yes
Release from LNG tank ship following collision (outside breakwater) with another ship of sufficient size and speed - 5 tanks fail	Yes	Yes
Release from LNG storage tank after plane crash	NA	No
Release from LNG storage tank after truck bomb	NA	No

* Details have been removed because this is considered to be Critical Energy Infrastructure Information (CEII) by the FERC

NA - Not Applicable

Table 4-12
Ability of Release Events to Allow Vapor Cloud Development
(Continued)

Release	Development of Flammable Cloud Following Accidental Release?	Development of Flammable Cloud Following Intentional Release?
Release from LNG storage tank after RPG	NA	Yes
Release from LNG tank ship after plane crash - 2 tanks fail	NA	No
Release from LNG tank ship after plane crash - 5 tanks fail	NA	No
Release from LNG tank ship after RPG	NA	Yes

NA - Not Applicable

4.7.1 Flammable Vapor Cloud Dispersion Calculations for Process Equipment Releases

The release caused by an accidental rupture of the process equipment F could result from an equipment failure that did not result in immediate ignition. If the failure had been intentionally caused by an explosive device (e.g., satchel charge), the release would be ignited and a torch fire would result.

The fluid from the process equipment F would be released under pressure and forms an aerosol composed of vapor and suspended liquid droplets. As described in Section 4.4.1, virtually none of the liquid reaches the ground. The aerosol flow rate is input to the momentum jet dispersion model contained in the CANARY software since DEGADIS cannot model this release.

The hazard footprint and vulnerability zone for the flammable vapor cloud following the accidental release from the process equipment F are presented in Figure 4-18.

Flammable cloud dispersion calculations for all process equipment releases listed in Table 4-11 were made using the CANARY software.

4.7.2 Flammable Vapor Cloud Dispersion Calculations for Storage Tank Failures Due to an Earthquake

It is extremely unlikely that an earthquake of the magnitude necessary to cause the failure of both LNG tanks would not create multiple immediate ignition sources for the ignition of any of the flammable vapors released in the terminal. If immediate ignition does not occur, it is not possible to know how far the cloud would drift before being ignited.

In the extreme case where all worst case conditions are combined;

low wind speed (2 m/s),
stable atmosphere (Pasquill-Gifford F), and
no immediate ignition sources,

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Figure 4-18

the flammable cloud only has one choice – it must drift over the open water in order to achieve it's maximum extent. Any travel inland would result in shorter travel distances due to ignition sources created by the earthquake event.

The vapor generation rate history calculated in Section 4.5.2 is used as input to the DEGADIS model. The DEGADIS model calculates the maximum flammable cloud travel distance over water to be 36,400 ft (6.9 miles). The cloud would require a little over three hours to travel this distance.

There are no credible arguments that would allow for a flammable cloud of this size to exist in the immediate neighborhood of multiple ignition sources caused by such a massive earthquake. However, in the context of this worst-case analysis study, the flammable vapor cloud travel defined by this case – over water without any portion of the cloud traveling inland – may be defined as possible but it certainly is not credible.

4.7.3 Flammable Vapor Dispersion Calculations from LNG Tank Ship Following Collision with the Breakwater

The evolution of a flammable cloud without ignition following a release from an LNG cargo tank following collision with the breakwater is a far more credible scenario than the generation of a large flammable cloud following an earthquake near the terminal. The generation of flammable vapor over the open water, with immediate ignition sources limited to the LNG tank ship itself, results in a scenario where the cloud might drift some distance before encountering an ignition source.

The vapor generation histories for the single LNG cargo tank and sequential LNG cargo tank failures described in Section 4.5.3 were input to the DEGADIS program. Under the worst case conditions defined for this work, the following flammable cloud travel distances and times (over water) were calculated.

LNG Tank Ship Collision with Breakwater Scenarios	Maximum Distance to Lower Flammable Limit	Cloud Travel Time (minutes) to Maximum Travel Distance
One tank failure	9,260 ft (1.75 miles)	45
Sequential failure of five tanks	19,330 ft (3.66 miles)	90

Flammable vapor cloud dispersion calculations were made for the cases identified in Table 4-11 under worst case atmospheric conditions. The flammable cloud travel distances achieved by the larger releases should be viewed with caution due to the number of factors that would prevent the development of such large clouds. Therefore, it would be incorrect to develop flammable vapor cloud vulnerability zones (circles) for the following releases:

- Earthquake caused failures of one or both LNG storage tanks
- Collision of LNG tank ship with breakwater (one or all cargo tanks fail)
- Collision of LNG tank ship with another ship near the harbor entrance (one or all cargo tanks fail)

The generation of vulnerability zones for these releases, as they pertain to the onshore or inland travel of a flammable vapor cloud, is defined by the site-specific characteristics of existing ignition sources, or those created due the initial failure mechanism. The evaluation of such an ignition source map and the construction of ignition probabilities as a function of cloud size and travel time is beyond the scope of this work. However, under no circumstances should the maximum cloud travel distances presented in Table 4-11 be applied as the inland or onshore travel distances of the eight scenarios listed above.

4.8 Vapor Cloud Explosion Overpressure Calculations

In an industrial environment such as the POLB, common ignition sources would be motor vehicles, diesel generators, electric switch boxes, arc welders, fired heaters, electric motors, or any electrical equipment not classified for use in a flammable environment. In situations when the drifting flammable cloud encounters an ignition source and begins to burn back, or flash back, towards the source of the release, overpressure will be generated by the burning process. In this analysis, the Baker-Strehlow model was used to calculate the magnitude of the overpressure . This model is based on the premise that the strength of the blast wave generated by a vapor cloud explosion (VCE) is dependent on the reactivity of the flammable gas involved; the presence (or absence) of structures such as walls that partially confine the vapor cloud; and the spatial density of obstructions within the flammable cloud [Baker, et al., 1994; 1998]. This model reflects the results of several international research programs on vapor cloud explosions, which show that the strength of the blast wave generated by a VCE increases as the degree of confinement and/or obstruction of the cloud increases. The following quotations are directly applicable to natural gas releases and natural gas vapors evolving from pools of LNG.

> *"On the evidence of the trials performed at Maplin Sands, the deflagration [explosion] of truly unconfined flat clouds of natural gas or propane does not constitute a blast hazard."* [Hirst and Eyre, 1982] (Tests conducted by Shell Research Ltd., in the United Kingdom.)

> *"Both in two- and three-dimensional geometries, a continuous accelerating flame was observed in the presence of repeated obstacles. A positive feedback mechanism between the flame front and a disturbed flow field generated by the flame is responsible for this. The disturbances in the flow field mainly concern flow velocity gradients. Without repeated obstacles, the flame front velocities reached are low both in two-dimensional and three-dimensional geometry."* [van Wingerdan and Zeeuwen, 1983] (Tests conducted by TNO in the Netherlands.)

> *"The current understanding of vapor cloud explosions involving natural gas is that combustion only of that part of the cloud which engulfs a severely congested region, formed by repeated obstacles, will contribute to the generation of pressure."* [Johnson, Sutton, and Wickens, 1991] (Tests conducted by British Gas in the United Kingdom.)

Researchers who have studied case histories of accidental vapor cloud explosions have reached similar conclusions.

> *"It is a necessary condition that obstacles or other forms of semi-confinement are present within the explosive region at the moment of ignition in order to generate an explosion."* [Wiekema, 1984]

> *"A common feature of vapor cloud explosions is that they have all involved ignition of vapor clouds, at least part of which, have engulfed regions of repeated obstacles."* [Harris and Wickens, 1989]

A review of the release scenarios that have the potential to develop drifting flammable vapor clouds finds that accidental releases in the process area of the terminal have the potential to be located in amongst the process piping and equipment and are afforded some degree of obstruction. The Baker-Strehlow model contained in CANARY was used to calculate the distances to the 1 psig overpressure level.

The ability of the larger flammable vapor clouds to reach a confined or congested area without ignition is governed by the same obstacles as presented in Section 4.7. If the leading edge of a large flammable cloud were to encounter a congested area, fill it with flammable vapor, and then find an ignition source inside or outside the congested area, the overpressure generated would be a function of the volume of the congested area. Flammable vapors outside the congested area would not significantly contribute to the overpressure generated.

Without the site-specific knowledge of each and every possible congested or obstructed area along the shoreline that could be reached by a drifting vapor cloud, it is impossible to calculate site-specific effects. However, the Baker-Strehlow model does provide information on the maximum overpressure levels that could be achieved by natural gas explosions under a variety of conditions.

For flammable natural gas mixtures in outdoor residential or commercial areas that have some degree of obstruction (e.g., parked cars) the maximum overpressure generated in the cloud would be approximately 1.09 psig. This would be the localized overpressure and cannot be applied to the body of the flammable cloud as the overpressure level will drop exponentially with distance from the obstructed area.

Using this information as a guide, the footprint of any overpressure map onto the shoreline near the LNG terminal will extend no further than the existing or created ignition sources. The exact mapping of such is beyond the scope of this work.

SECTION 5
POTENTIAL IMPACTS TO NEIGHBORING FACILITIES

5.1 Neighboring Facilities

The proposed LNG import terminal is located on the west side and south end of Pier T in the Port of Long Beach. One task defined for this work was to calculate the potential impacts to neighboring industrial facilities, both current and proposed. These impacts were to be calculated for the worst-case events, both accidental and intentional, identified in Section 2.

Two facilities of particular interest are the existing oil berth at T-121 and the proposed oil berth at T-124. These two facilities are identified on Figure 5-1.

5.2 Impact Levels on Industrial Equipment

The potential impact on people from exposure to radiant flux levels from a fire, as well as overpressure levels following the ignition of a flammable cloud, were quantified in Section 4. Evaluating the impact of radiant and overpressure hazards on industrial equipment located near the LNG terminal requires the use of a different set of hazard endpoints (i.e., radiant flux and explosion overpressure levels) than those used to determine impacts on people.

5.2.1 Vulnerability of Structures and Plant Equipment to Radiant Energy

Structures composed of noncombustible materials (e.g., metal storage tanks) can be weakened, resulting in damage or complete destruction, if the radiant heat flux is high enough and persists long enough to heat the structure to its damage point.

Part 193 of Title 49 of the Code of Federal Regulations (commonly referred to as 49 CFR 193), is the United States Department of Transportation (U.S. DOT) federal standard for LNG facilities in the U.S. [DOT]. Through reference to an industry standard, NFPA 59A – *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)*, 49 CFR 193 sets 10,000 Btu/(hr$\cdot$ft^2) (30 kW/m^2) as the limiting heat flux at the demarcation line between land area controlled by the LNG facility and land areas controlled by other parties. The intent is to ensure that the heat flux from code-specified design spill fires will not cause failures of steel-framed buildings and similar industrial-type structures outside the LNG facility. Therefore, when analyzing the effects of worst-case fires that can be much larger than the design spill fires, it is reasonable to use 10,000 Btu/(hr$\cdot$ft^2) as the lower limit for radiant heat flux calculations in an industrial area. Non-combustible structures outside the 10,000 Btu/(hr$\cdot$ft^2) isopleth should not be heavily damaged by the fire, and those within the 10,000 Btu/(hr$\cdot$ft^2) isopleth will withstand several minutes of exposure to the radiant heat before failing.

5.2.1.1 Radiant Flux Endpoint Criteria

As shown in Section 4, the large scale fires evaluated under worst-case atmospheric conditions have the potential to affect people in areas outside the LNG terminal fence line. When evaluating a person's possible exposure to a radiant flux level that would cause skin burns after a short period of time, the use of

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vulnerability zones was employed. Vulnerability zones identify the total area in which, under some circumstances, people could be exposed to a radiant level greater than or equal to that necessary to cause skin burns (e.g., 1,600 Btu/(hr·ft^2) for 30 seconds).

The same type of approach can be used to identify the potential radiant impact to the industrial areas neighboring the LNG terminal. For the purposes of this study, the radiant endpoint selected for evaluation is 10,000 Btu/(hr·ft^2). This level of radiant heat will have the following effect on materials in an industrial area.

- Exposure to 10,000 Btu/(hr·ft^2) for 15 to 20 minutes will cause wooden buildings to ignite. [HUD, 24 CFR 51]
- Exposure to 10,000 Btu/(hr·ft^2) for several minutes will damage steel structures. [HUD, 24 CFR 51]

5.2.1.2 Radiant Energy Vulnerability Zones – Industrial Equipment Impact

Using the same pool fire and torch fire models as defined in Section 4 for the selected accidental and intentional events, the distance to the 10,000 Btu/(hr·ft^2) radiant flux level was calculated. The results for these calculations (the radii of the vulnerability zones) are presented in Table 5-1. Equipment within the vulnerability zones identified in Table 5-1 have the possibility, under certain weather conditions (e.g., the wind blowing toward the equipment), to be exposed to radiant impacts that would cause their structural failure.

As can be seen from Table 5-1 and Figure 5-1, several of the larger events have the potential to impact the existing oil berth (T-121, 1,300 ft from a point centered between the two LNG storage tanks) and the proposed berth (T-124, 750 ft from a point centered between the two LNG storage tanks). Several of the radiant vulnerability zones are presented in Figures 5-2 through 5-11.

From a review of these vulnerability zones it can be concluded that if one of the LNG release events were to occur and a fire ensue, that significant damage to areas within T-124 and T-121 is possible. All the large releases involving LNG have the potential to last from tens of minutes to several hours, depending on the size of the hole through which the LNG is being released. In all cases, the duration of the fire is closely linked to the duration of the release. The reason for this is that LNG liquid spread is unrestricted in most cases and the FERC spreading model allows the LNG to spread to very thin pool thickness. Thus, once the source of LNG is exhausted (there is no more LNG to release), the fire consumes the remaining LNG in a very short time.

5.2.2 Vulnerability of Structures and Plant Equipment to Overpressure

Gas-phase explosions are the result of very rapid combustion of flammable vapor clouds. One characteristic of all explosions is the sudden (nearly instantaneous) release of energy. In gas-phase explosions, a portion of the released energy manifests itself as a pressure wave.

Pressure waves created by explosions can travel through any solid, liquid, or gas, including the earth, water, and air. For the purposes of this study, pressure waves in air are of most interest since vapor cloud explosions occur in the air.

Table 5-2 lists the approximate overpressures required to produce specific levels and types of damage to equipment, buildings, and other structures commonly found in industrial areas. For example, a peak side-on overpressure of 20.7 kPa (3 psi) will cause typical oil storage tanks to fail.

Table 5-1
Consequence Analysis Results – Equipment Impact
Facility = LNG Import Terminal at Port of Long Beach, California

Cause of Release (A) = Accidental (I) = Intentional		Distance (ft) to 10,000 Btu/(hr·ft^2) Radiant Flux Level	Measured From	Figure	Maximum Overpressure Achieved	Distance (ft) to 2.3 psig
(A) (I)	Rupture of process equipment - location A*	140	Release Point	—	1.09	NA
(A) (I)	Rupture of process equipment - location B*	160	Release Point	—	3.06	130
(A) (I)	Rupture of process equipment - location C*	360	Release Point	—	1.86	NA
(A) (I)	Rupture of process equipment - location D*	160	Release Point	—	1.86	NA
(A) (I)	Rupture of process equipment - location E*	400	Release Point	—	1.09	NA
(A) (I)	Release from process equipment - location F*	600	Release Point	Figure 5-2 Figure 5-12	3.06	130
(A) (I)	Release from process equipment - location G*	260	Release Point	—	3.06	130
(A)	Release from LNG storage tanks following earthquake	3,780	Center of LNG Pool on Water	Figure 5-3	1.09	NA
(A)	Release from LNG tank ship following collision with breakwater - 1 tank fails	990	Center of LNG Pool by Tank Ship	Figure 5-4	1.09	NA
(A)	Release from LNG tank ship following collision with breakwater - 5 tanks fail	1,480	Center of LNG Pool by Tank Ship	Figure 5-5	1.09	NA

NA = Explosion overpressure level not achieved
DNA = Does not apply – vapor cloud formation is not possible following initiating event
* = Details have been removed because this is considered to be Critical Energy Infrastructure Information (CEII) by the FERC

Table 5-1
Consequence Analysis Results – Equipment Impact
Facility = LNG Import Terminal at Port of Long Beach, California
(Continued)

Cause of Release (A) = Accidental (I) = Intentional		Distance (ft) to 10,000 Btu/(hr·ft^2) Radiant Flux Level	Measured From	Figure	Maximum Overpressure Achieved	Distance (ft) to 2.3 psig
(A) (I)	Release from LNG tank ship following collision (outside breakwater) - 1 tank fails	1,325	Center of LNG Pool on Water	—	1.09	NA
(A) (I)	Release from LNG tank ship following collision (outside breakwater) - 5 tanks fail	1,495	Center of LNG Pool on Water	—	1.09	NA
(I)	Release from LNG storage tank after plane crash	1,265	Center of LNG Pool on Water	Figure 5-6	DNA	DNA
(I)	Release from LNG storage tank after truck bomb	3,090	Center of LNG Pool on Water	Figure 5-7	DNA	DNA
(I)	Release from LNG storage tank after RPG	80	LNG Pool by Tank	—	1.09	NA
(I)	Release from LNG tank ship after plane crash - 2 tanks fail	1,610	Center of LNG Pool by Tank Ship	Figure 5-8	DNA	DNA
(I)	Release from LNG tank ship after plane crash - 5 tanks fail	1,650	Center of LNG Pool by Tank Ship	Figure 5-9	DNA	DNA
(I)	Release from LNG tank ship after boat bomb - 1 tank fails	1,385	Center of LNG Pool by Tank Ship	Figure 5-10	DNA	DNA
(I)	Release from LNG tank ship after boat bomb - 5 tanks fail	1,635	Center of LNG Pool by Tank Ship	Figure 5-11	DNA	DNA
(I)	Release from LNG tank ship after RPG	65	Center of LNG Pool by Tank Ship	—	1.09	NA

NA = Explosion overpressure level not achieved
DNA = Does not apply – vapor cloud formation is not possible following initiating event

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Table 5-2
Damage Produced by Blast [Clancey, 1972]

Overpressure (psig)	Damage
0.02	Annoying noise (137 dB if of low frequency 10-15 Hz)
0.03	Occasional breaking of large glass windows already under strain
0.04	Loud noise (143 dB), sonic boom glass failure
0.1	Breakage of small windows under strain
0.15	Typical pressure for glass breakage
0.3	"Safe distance" (probability 0.95 no serious damage beyond this value); projectile limit; some damage to house ceilings; 10% window glass broken
0.4	Limited minor structural damage
0.5 - 1.0	Large and small windows usually shattered; occasional damage to window frames
0.7	Minor damage to house structures
1.0	Partial demolition of houses, made uninhabitable
1 - 2	Corrugated asbestos shattered; corrugated steel or aluminum panels, fastenings fail, followed by buckling; wood panels (standard housing) fastenings fail, panels blown in
1.3	Steel frame of clad building slightly distorted
2	Partial collapse of walls and roofs of houses
2 - 3	Concrete or cinder block walls, not reinforced, shattered
2.3	Lower limit of serious structural damage
2.5	50% destruction of brickwork of houses
3	Heavy machines (3,000 lb) in industrial building suffered little damage; steel frame building distorted and pulled away from foundations
3 - 4	Frameless, self-framing steel panel building demolished; rupture of oil storage tanks
4	Cladding of light industrial buildings ruptured
5	Wooden utility poles snapped; tall hydraulic press (40,000 lb) in building slightly damaged
5 - 7	Nearly complete destruction of houses
7	Loaded train wagons overturned
7 - 8	Brick panels, 8-12 inches thick, not reinforced, fail by shearing or flexure
9	Loaded train boxcars completely demolished
10	Probable total destruction of buildings; heavy machine tools (7,000 lb) moved and badly damaged, very heavy machine tools (12,000 lb) survived
300	Limit of crater lip

5.2.2.1 Explosion Overpressure Endpoint Criteria

As shown in Section 4, the vapor cloud explosion overpressures have little potential to adversely affect people in areas outside the immediate LNG terminal. This is primarily due to the inability of the drifting cloud to penetrate the nearby shoreline without finding an ignition source.

For purposes of this study, 2.3 psi overpressure was selected as the lower limit for evaluating the possible overpressure impacts on the neighboring industrial sites. Overpressures lower than 2.3 psig would not be expected to produce significant damage to industrial equipment.

5.2.2.2 Explosion Overpressure Vulnerability Zones – Industrial Equipment Impact

As noted in Section 4, the maximum overpressure generated by a flammable cloud of natural gas that drifted into a moderately obstructed area, such as a parking lot, was 1.09 psig. Thus, if this type of event were to occur, the overpressure levels would be below those required to produce significant structural damage in industrial areas.

Using the same explosion overpressure methodology as defined in Section 4 for the selected accidental and intentional events, the distance to the 2.3 psig overpressure level was calculated. The results for these calculations (the radius of each vulnerability zone) are presented in Table 5-1. It should be noted in Table 5-1 that several of the releases in the gas processing area have the potential to generate maximum overpressures in the range of 3 psig. This is a result of a more reactive fluid mixture (ethane, propane, etc.) being released in obstructed areas within the process area (e.g., congested areas with pipe racks, etc.). The majority of the large releases identified in this work resulted in vapor clouds composed primarily of methane, defined as a low reactivity material. The 2.3 psig overpressure vulnerability zone for a release from process equipment F is presented in Figure 5-12 as an example of a more reactive material.

None of the vapor cloud explosion events evaluated resulted in overpressures high enough to fail the oil storage tanks proposed for T-124. According to Clancey [Clancey, 1972], an overpressure in excess of 3 psig would be necessary in order to rupture oil storage tanks.

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SECTION 6
WORST-CASE HAZARDS ASSOCIATED WITH OTHER FLAMMABLE FUEL FACILITIES

6.1 Flammable Fuel Facilities

The potential worst-case impacts associated with the proposed LNG import terminal in the Port of Long Beach can be compared to the potential worst-case impacts of other flammable fuel facilities. Previously completed studies on three flammable fuel facilities were used for this comparison. It should be noted that terrorist-induced failures were explicitly considered in only one of the three previous studies. However, as was the case when evaluating several of the events in the LNG import terminal, several of the events evaluated in the other flammable fuel facilities would have the same impact whether the initial release was accidental or intentional in nature.

The three flammable fuel facilities can be briefly described as follows.

Facility #1 — The largest refrigerated propane terminal in northen California. This terminal has refrigerated propane storage tanks, pressurized ambient temperature storage tanks (bullets), and both railcar and tank truck loading.

Facility #2 — Several petroleum product tank farms, located in southern California, with large capacity storage tanks containing a variety of petroleum products.

Facility #3 — 10 million tons per annum (10 mtpa) LNG import terminal in Mexico. This terminal will have a peak natural gas generation capacity of 2.4 billion cubic feet per day (2.4 bcfd).

None of the three facilities stores or processes any significant amount of toxic materials. Thus, the comparison of potential hazards between the three facilities and the LNG import terminal is based solely on the flammable nature of the hydrocarbons processed and stored in each.

In addition to the three facilities described above, the flammable hazards associated with a range of LPG storage vessels that are located throughout the Long Beach area were calculated. The LPG vessel sizes ranged from a common 5 gallon backyard grill propane bottle to a 12,500 barrel LPG storage sphere that located in refinery.

6.2 Propane Storage Terminal, Elk Grove, California

6.2.1 Description of the Major Components in the Propane Terminal

The Suburban Propane Elk Grove facility [COEG, 2000] receives pressurized ambient temperature liquid propane from tank trucks and railcars, stores both ambient temperature and refrigerated liquid propane, and loads ambient temperature propane for off-site transport. On average, approximately 120,000 gallons of propane are handled at the facility each day by tank truck and railcar.

The major equipment at the facility consists of four 60,000-gallon pressurized, ambient temperature propane storage vessels (bullets); two 12,000,000-gallon refrigerated, low pressure storage tanks; tank truck and railcar loading/unloading stations; and a propane refrigeration system. The propane storage bullets are nominally 12 feet in diameter and 91 feet long, placed horizontally on concrete supports about 5 feet above the ground. The large refrigerated propane storage tanks are approximately 146 feet in diameter and 122 feet tall.

Propane is received at the facility as pressurized, ambient temperature liquid carried in tank trucks or railcars. The tank trucks have a typical capacity of 10,000 gallons and the railcars a typical capacity of 33,000 gallons. The large refrigerated storage tanks serve as storage reservoirs that can absorb the seasonal swings in propane demand. Liquid propane can be moved from the refrigerated storage tanks to the pressurized bullets using centrifugal pumps.

6.2.2 Potential Hazards Associated with the Propane Terminal

For flammable fuel facilities that process and store refrigerated and pressurized flammable fluids, the common hazards are:

- Torch fires (gas and liquefied gas releases)
- Flash fires (liquefied gas releases)
- Pool fires (liquefied gas releases)
- Vapor cloud explosions (gas and liquefied gas releases)
- BLEVEs (major failures of tank trucks, railcars, or aboveground pressurized storage tanks)

With the exception of the BLEVE, all the potential hazards associated with the propane terminal are present in the proposed LNG import terminal. The BLEVE event has the potential to occur in the propane terminal due to the storage of propane in pressure vessels (bullets, railcars, and tank trucks). It should be noted that BLEVE's are not possible in the proposed LNG import terminal as none of the flammable materials are stored under pressure, thus there are no pressurized storage vessels.

6.2.3 Potential Release Events Associated with the Propane Terminal

The propane terminal was the subject of a foiled sabotage effort by two US citizens in 1999. Due to concern about the consequences of such possible events, both accidental and intentional releases of propane were evaluated. The worst-case consequence results from this study are presented in Table 6-1. Whether the release was caused by accidental or intentional means, once the release occurs, the methodologies used to calculate the extents of the potential impacts were the same. For example, whether a pipe fails due to a bad weld or due to detonation of an explosive charge placed beside it, the resulting fires would be identical. In Table 6-1, the events and the consequence analysis results associated with that event are identified as being produced by an accidental (A) or an intentional (I) event.

In general, the largest potential hazards in the propane facility are associated with pool fires following a significant release from the refrigerated propane storage tanks or a BLEVE of one of the pressurized storage bullets. However, the largest potential hazard is the flash fire associated with a large release from both refrigerated propane tanks. If an earthquake of sufficient magnitude to fail the tanks were to occur, the flammable vapor cloud travel distances reported should not be considered credible due to the inability to avoid the numerous ignition sources generated by the earthquake. In other words, it would be expected that any one of the many available ignition sources (e.g., downed power lines) in the immediate area would ignite the flammable vapors. Once ignited, a pool fire would result. If this were to occur, the flammable cloud distances listed in Table 6-1 could not be achieved as the cloud would be ignited before it reached the listed distances. It is unlikely that the cloud would extend any significant distance past the facility fence line.

Table 6-1
Consequence Analysis Results
Facility = Propane Terminal Near Sacramento, California

Cause of Release (A) = Accidental (I) = Intentional		Distance (ft) to Radiant Flux Level 1,600 Btu/(hr·ft²)		Measured From	Distance (ft) to 1 psig Overpressure		Distance (ft) to LFL	
(A)	Release from two 12,000,000 gallon refrigerated propane storage tanks following earthquake	(A)	1,320	Center of diked area for both tanks	(A)	525	(A)	26,750
(A) (I)	Rupture of bottom connection on 12,000,000 gallon refrigerated propane storage tank	(A) (I)	1,230	Center of dike	(A) (I)	525	(A)	700
(A) (I)	Rupture of bottom connection on 60,000 gallon propane bullet	(A) (I)	230	Release point	(A) (I)	525	(A)	650
(A) (I)	BLEVE of 60,000 gallon propane bullet	(A) (I)	1,900	Release point		—		—
(A) (I)	BLEVE of 33,000 gallon propane railcar	(A) (I)	1,550	Release point		—		—

Comparison of the worst-case hazards for the propane facility and the proposed LNG import terminal finds that the pool fire radiant impact distances and the flash fire impact distances to be similar for the land-based releases. This is primarily due to the fact that the propane is stored in a cryogenic state similar to the LNG in the proposed import terminal. The behavior of propane vapor clouds evolving off a liquid pool is similar to the behavior of natural gas evolving off a pool of LNG.

The biggest difference between the two terminals has to do with the method of shipping the propane or LNG into or out of the terminals. The propane facility employs pressurized railcars and tank trucks while the LNG terminal will use insulated tank ships and tank trucks. The differences manifest themselves not only in the size of a potential hazard due to transportation inventory (LNG is larger) but also with the frequency of the possible events (propane shipping is far more frequent).

6.3 Petroleum Product Bulk Storage Terminals, Southern California

6.3.1 Description of the Terminals

The subjects of this study were several bulk storage facilities associated with Equilon's Wilmington Refinery CARB Phase 3 Project [SCAQMD, 2001]. The majority of the bulk terminal changes involved changing the products that the storage tanks contained. These modifications involved atmospheric storage tanks.

The four bulk terminals selected for evaluation are all located in southern California. The products stored at the sites include crude oil, jet fuel, kerosene, gasoline, and ethanol. The products are stored in tanks with a range of capacities, several as large as 100,000 barrels.

The common hazards associated with the storage of ambient temperature flammable hydrocarbons in atmospheric storage tanks are:

- Flash fires (vapors evolving off liquid pools)
- Pool fires

6.3.2 Potential Release Events Associated with the Bulk Terminals

Several of the worst-case consequence results from the analysis of the bulk terminals are presented in Table 6-2. Intentional acts were not considered in the original analysis. However, if they had been, the resulting consequences would be no larger than the consequences associated with the accidental events considered in Table 6-2.

The largest potential hazards are associated with pool fires in the impounding area following a significant release from one or more storage tanks. Unlike the propane terminal, vapors evolving off the hydrocarbon fluids in the terminal (crude oil, jet fuel) do not form large vapor clouds. Often the extent of the flammable vapors will only be slightly outside the confined pool. Thus, if an ignition source is found, a pool fire is the result. There will be no significant overpressure generated by the ignition of the petroleum products in the tank farm environment.

The potential fire impacts from any one storage tank in any of the bulk terminals is smaller than the fire impacts due to either one of the proposed LNG tanks. This is primarily due to inventory and site layout. The physical properties of the materials stored in the bulk terminals (jet fuel, gasoline, etc.) have lower burning rates and produce "smokier" flames. These two characteristics result in shorter fires that radiate less thermal energy.

Table 6-2
Consequence Analysis Results
Facility = Flammable Fuel Depots, Southern California

Cause of Release (A) = Accidental (I) = Intentional	Distance (ft) to Radiant Flux Level 1,600 Btu/(hr·ft^2)	Measured From	Distance (ft) to 1 psig Overpressure	Distance (ft) to LFL
(A) Morman Island Terminal - Jet Fuel - Tank top fire	(A) 215	Center of tank	—	—
(A) (I) Morman Island Terminal - Jet Fuel - Dike fire	(A) (I) 350	Center of dike	—	—
(A) Signal Hill Terminal - Gasoline - Tank top fire	(A) 175	Center of tank	—	—
(A) (I) Signal Hill Terminal - Gasoline - Dike fire	(A) (I) 595	Center of dike	—	—
(A) Colton Terminal - Gasoline - Tank top fire	(A) 140	Center of tank	—	—
(A) (I) Colton Terminal - Gasoline - Dike fire	(A) (I) 485	Center of dike	—	—
(A) Rialto Terminal - Diesel - Tank top fire	(A) 95	Center of tank	—	—
(A) (I) Rialto Terminal - Diesel - Dike fire	(A) (I) 315	Center of dike	—	—

6.4 LNG Import Terminal, Mexico

6.4.1 Description of the Major Components in the LNG Import Terminal

The Altamira LNG Import Terminal has been proposed for the eastern coast of Mexico. The project has undergone regulatory review in Mexico during which time a number or safety, consequence, and risk analysis studies were completed [Shell and El Paso Consortium, 2001]. The LNG import terminal will receive LNG from tank ships, store the LNG in large insulated storage tanks, and regasify the LNG using open rack vaporizers. In the final phase of the project, the terminal will have a nominal throughput of 10 million tonnes[1] per annum (mpta).

The facility is comprised of several main components.

- LNG tanker berthing facility and unloading arms.
- Large capacity atmospheric LNG storage tanks.
- In-tank and external LNG pumps.
- Open rack vaporizers.
- Vapor handling equipment.

6.4.2 Potential Hazards Associated with the LNG Import Terminal

The potential hazards associated with the LNG import terminal are identical to those identified in Section 4 for the proposed SES LNG terminal in the Port of Long Beach.

- Torch fires (gas and liquefied gas releases)
- Flash fires (gas and liquefied gas releases)
- Pool fires (liquefied gas releases)
- Vapor cloud explosions (gas and liquefied gas releases)

6.4.3 Potential Release Events Associated with the LNG Terminal

The consequence and risk analysis studies completed for the LNG terminal were focused on accidental releases of LNG and natural gas from the onshore terminal. Thus, release events involving the transport of LNG by tank ship were not included in this study. Similarly, intentional acts, due to sabotage or terrorism were not included in this study.

A summary of the largest worst-case consequences following the largest release events evaluated in the study is presented in Table 6-3. The maximum flammable cloud travel distance listed in Table 6-3 is associated with an earthquake-induced failure of an LNG storage tank. As described in the evaluation of the SES LNG import terminal and the propane terminal in Section 5.2, this should not be considered a credible event since multiple ignition sources would exist in the immediate area. These ignition sources would prevent any significant travel of the vapor cloud prior to ignition.

[1] 1 tonne = 1000 kilograms = 2204 lb = 1.102 tons

Table 6-3
Consequence Analysis Results
Facility = LNG Import Terminal, Altamira, Mexico

Cause of Release (A) = Accidental (I) = Intentional		Distance (ft) to Radiant Flux Level 1,600 Btu/(hr·ft^2)		Measured From	Distance (ft) to 1 psig Overpressure		Distance (ft) to LFL	
(A)	Rupture of process equipment - location W*	(A)	600	Release point		—	(A)	3,770
(A)	Rupture of process equipment - location X*	(A)	300	Release point	(A)	200	(A)	570
(A)	Rupture of process equipment - location Y*	(A)	140	Release point	(A)	200	(A)	620
(A)	Rupture of process equipment - location Z*	(A)	420	Release point		—	(A)	375
(A)	Release from LNG storage tank following earthquake	(A)	1,240	Center of tank	(A)	200	(A)	21,200

* Details have been removed because this is considered to be Critical Energy Infrastructure Information (CEII) by the FERC

6.5 Comparison of Flammable Fuels Facilities Potential for Off-site Impacts

Each of the three flammable fuels facilities evaluated has the potential to generate offsite impacts if a significant release of one or more of the fuels stored or processed in the facility were to occur. In each facility where a intentional release was evaluated, the impacts resulting from an intentional release were no larger than the impacts associated with one or more releases that could occur accidentally.

Table 6-4
Comparison of Worst-Case Impacts from Four Flammable Fuel Facilities

Facility	Offsite Impacts and Maximum Hazard Impact Distance		
	Radiant (1,600 Btu/($hr \cdot ft^2$))	Flash Fire (LFL)	Overpressure (1 psig)
LNG Import Terminal, Long Beach, California	Yes max. distance = 8,610 ft	Yes max. distance = 34,600 ft	Yes max. distance = 320 ft
Propane Terminal, Northern California	Yes max. distance = 1,900 ft	Yes max. distance = 26,750 ft	Yes max. distance = 525 ft
Bulk Storage Terminals, Southern California	Yes max. distance = 595 ft	Yes max. distance = 675 ft	No
LNG Import Terminal, East Coast of Mexico	Yes max. distance = 1,240 ft	Yes max. distance = 21,200 ft	Yes max. distance = 200 ft

As can be seen from a review of Table 6-4, all four facilities have the potential to produce off-site impacts. The common misconception that explosions in flammable fuel facilities produce significant off-site explosion impacts is not supported by the modeling performed in this study, nor the historical record [Mahoney, 1997].

As described in Section 4.8, the inability of an evolving flammable vapor cloud to travel significant distances before finding an ignition source reduces the significance of the flammable vapor cloud travel distances in industrial or populated areas. Therefore, the flammable vapor cloud travel distances listed in Table 6-4 should be thought of as theoretical maximums rather than realistic assessments.

This leaves the comparison of fire radiation impacts (pool fires and torch fires) as the best method for comparing the impacts among the facilities. When this comparison is made, the maximum radiant impacts from the four facilities range from 595 to 8,610 feet from the fire source. In all four facilities, these worst-case radiant impacts have the potential to extend past the facility property line.

In the specific case of the proposed LNG import terminal in the Port of Long Beach, only two of the events evaluated have the potential to produce radiant impacts past the industrial area defined by the POLB boundary line. The largest radiant impact distance, 8,610 ft to 1,600 Btu/($hr \cdot ft^2$) [second degree skin burns], results from an earthquake of sufficient magnitude to fail both LNG storage tanks and the security wall surrounding the tanks. This failure allows a significant portion of the LNG to reach the water. Following ignition, the fire column (as defined by the FERC fire model) can produce 1,600 Btu/($hr \cdot ft^2$) slightly past the eastern POLB boundary line. When reviewing this scenario, four things should be kept in mind.

1. An earthquake of the magnitude necessary to fail the full containment LNG storage tank, would be more than sufficient to level every structure in the Port of Long Beach as well as the City of Long Beach.

2. In addition to an earthquake of sufficient magnitude occurring that fails both LNG tanks, a high wind would have to be blowing in order for the fire to impact any area outside the POLB boundary.

3. The FERC fire model employed to make this calculation does not have an ability to account for the lack of oxygen available to the core of such a large fire. The model is believed [FERC, 2004; Raj, 2004] to significantly overestimate the height and surface flux of the flame, thus overestimating the potential impacts.

4. This accidental event, although defined as possible, would be considered incredible when performing risk assessments and would not be used as a benchmark for siting calculations.

The second fire event that has the ability to produce 1,600 Btu/(hr·ft^2) [second degree skin burns] impacts past the POLB boundary is from a fire following a truck bomb that fails one of the LNG storage tanks as well as the security wall. This event, although intentional in nature, results in a fire similar to, but smaller than, the fire associated with the earthquake. In this case, the 1,600 Btu/(hr·ft^2) impact zone does not extend as far as the earthquake-induced failure since the LNG inventory is less (only one tank fails). However, issues 2 and 3 listed above would also apply to this scenario.

All the remaining LNG fire events evaluated for this study (those associated with terminal operations, storage, and LNG tank ship movements and operations) have no fire radiation impacts (second degree skin burns) that extend past the POLB boundary. This is true whether the initiating event is accidental or intentional.

6.6 Fire Hazards Associated With Storage of LPG in the Long Beach Area

Many residents of the Long Beach are aware of the use, transportation, and storage of LPG. LPG (liquid petroleum gas) is stored and used in vessels as small as 5 gallons. The 5 gallon tanks are commonly used within backyard bar-b-que grills. Residents in Long Beach can exchange the 5 gallon tanks at local distribution centers (often the neighborhood gas station).

Similar to the 5 gallon bar-b-que tank, many mobile homes and travel trailers have 35 gallon LPG tanks incorporated into their design. These tanks are attached to the exterior of the truck or trailer and travel the local roadways without restriction.

LPG is commonly transported over the local highways in tanks that include:

- Converted-fuel vehicles (LPG for fuel instead of gasoline or diesel), 80 gallon tank capacity
- LPG delivery truck (bobtail design), 4,000 gallon tank
- LPG transport truck (semi-trailer design), 10,000 gallon tank

Another type of LPG storage vessel that is more common in rural areas is a 1,000 gallon storage tank that is used for cooking, water heating, and home heating fuel. These tanks are often located beside the residence.

In refineries and gas plants it is not uncommon to find LPG storage vessels ranging in size from 30,000 to 60,000 gallon. Cylindrical vessels are often used to store inventories in this range. When larger quantities of LPG are stored, spherical vessels are often used. The capacities of these spherical vessels will range up to 12,500 barrels (528,000 gallons).

Although LPG is a flammable fuel like natural gas, the fact that it is stored as a liquid under pressure (as opposed to refrigerated like LNG), poses additional hazards that are not possible with the storage and use of LNG and natural gas. The largest and most dramatic of these is a Boiling Liquid Expanding Vapor Explosion (BLEVE). ...

A BLEVE (Boiling Liquid Expanding Vapor Explosion) is defined as the catastrophic failure of a pressure vessel, occurring at a time when the temperature of the liquid in the vessel is well above its boiling temperature at normal atmospheric pressure (i.e., the liquid is superheated). Most BLEVEs are caused by the vessel becoming overheated and weakening as a result of being in contact with the flames from an external fire. If parts of the vessel become too hot and too weak, the vessel will fail catastrophically. When this occurs, some portion of the superheated liquid will flash to vapor. The vapor will expand and shatter most of the remaining liquid into drops, and propel them away from the vessel. In most cases, the resulting mixture of air, vapor, and liquid drops will be ignited by the external fire, resulting in a fireball. The fireball will exist for a brief time, typically from 2 to 30 seconds, depending on the amount of liquid that was in the vessel. During its brief existence, the fireball will emit a large amount of radiant energy. This thermal radiation is the primary hazard created by a BLEVE.

When a BLEVE occurs, the distance from the failed vessel to a point where second-degree skin burns would be experienced by an exposed person can be calculated. For the purposes of comparison, a BLEVE calculation was performed for each of the LPG vessels described above. The results are presented in Table 6-5.

Table 6-5
Radiant Impact Distances for
Common LPG Storage and Transport Vessels

Propane Tank Description	Capacity (gallons)	Distance to 2nd Degree Skin Burns (feet)
Backyard bar-b-que grill tank	5	21
Mobile home propane tank	35	55
Pickup truck propane tank (automobile fuel conversion)	80	77
Farm house propane tank (heat and hot water)	1,000	252
Bobtail propane delivery truck	4.000	450
Semi-trailer propane tank	10,000	657
Railroad propane tankcar	33,000	1,069
LPG bullet storage (refinery, gas plant)	60,000	1,360
LPG sphere storage (refinery)	528,000	3,223

A review of the BLEVE results in Table 6-5 shows that BLEVEs of the larger LPG vessel result in radiant impact distances similar in size as many of the radiant zones evaluated for the LNG terminal. It should be kept in mind that BLEVEs are not influenced by the wind and their hazard zones are round whereas a radiant zone formed by an LNG pool fire is influenced by the wind and is only round under calm conditions (not the worst case). Thus, a BLEVE impact zone with a smaller radius will affect the same total area an LNG pool fire with a larger downwind distance reach.

6.7 Comparison of Risk

To put this type of evaluation in perspective, it is instructive to look at the types of risks people are ordinarily exposed to during day-to-day life. Table 6-6 lists the risks a citizen of Long Beach might be exposed to each and every day. As can be seen in the table, there voluntary risks (driving a car) and involuntary risks (dying from influenza) that are higher than the risk of injury that may result from living near the proposed LNG import terminal in the POLB.

In reviewing the results in Table 6-6, two issues should be kept in mind. The statistics from the National Safety Council are for fatalities and the risks outside the POLB property line are for injury. Thus, the risk levels for the LNG terminal are overstated when viewed in this context. Secondly, the development of the successful terrorist probability is based upon a successful terrorist event occurring in any of the 12,711 facilities in the US EPA data base, not just the POLB facility. Thus, if the probability of a successful terrorist attack was weighted toward a “good target” (as defined by the US EPA data), the probability values associated terrorist-induced events in the proposed LNG terminal in the POLB would be less.

Table 6-6
Individual Risk of Early Fatality by Various Causes
[National Safety Council, 1997]

Hazard	Approximate Individual Risk of Early Fatality	
	Probability/Year	One Chance in
Heart disease	2.76×10^{-3}	360
Cancer	2.01×10^{-3}	495
Stroke	5.77×10^{-4}	1,730
All accidents	3.52×10^{-4}	2,840
Pneumonia and influenza	3.07×10^{-4}	3,260
Motor vehicle	1.63×10^{-4}	6,125
Homicide	9.25×10^{-5}	10,800
Falls	5.31×10^{-5}	18,820
Poisoning by solids and liquids	3.69×10^{-5}	27,075
Pedestrian death by motor vehicle	2.30×10^{-5}	43,500
Drowning	1.50×10^{-5}	68,035
Fires and burns	1.21×10^{-5}	82,920
Suffocation by ingesting food or object	1.13×10^{-5}	88,450
Firearms	5.28×10^{-6}	189,530
Poisoning by gas or vapor	2.26×10^{-6}	442,235
Electric current	2.11×10^{-6}	473,000
Rail travel	1.45×10^{-6}	687,400
Scheduled air travel	5.99×10^{-7}	1,668,810
Cataclysmic storms and floods resulting from storms	4.03×10^{-7}	2,479,800
Lightning	3.16×10^{-7}	3,158,800
Bee strings and snake bites	2.37×10^{-7}	4,211,750
Cataclysmic earth movements and ruptures	1.73×10^{-7}	5,768,300
Accidental release of LNG from proposed LNG terminal, which produces second degree burns outside of POLB boundary	*1.00×10^{-7}*	*10,000,000*
Intentional release of LNG from proposed LNG terminal, which produces second degree burns outside of POLB boundary	*1.44×10^{-8}*	*69,600,000*

SECTION 7
CONCLUSIONS

7.1 Limitations of Study

The overall scope and execution of the study is limited by two restrictions. First, the study is not a full quantitative risk analysis since it was defined to evaluate only the worst-case releases. Thus, not all possible events are identified, quantified, and incorporated into the study. The events evaluated in this study cover a range of the largest accidental and intentionally-induced releases that could occur in the LNG import terminal and LNG tank ship operations. The study is not designed to be all inclusive, rather it is targeted at defining a set of representative worst-case impacts.

Secondly, all the data used to develop the releases, resultant consequences, and associated probabilities are drawn from publicly available resources. No use of proprietary, confidential, or not-to-be-publicly disclosed information was used in this study.

7.2 Development of Flammable Fuel Release Sequences and Probabilities

The identification of terminal components that may fail due to an accidental failure was made using a formal review process coupled with historical data and Quest's experience in the LNG industry. Many of the largest accidental releases identified have never occurred in the industry, but they are still considered credible.

Identifying the largest releases that could be effected by intentional acts required a less structured approach than that used for the accidental releases. Several potential terrorist-executed acts that came out of public hearings and comment letters were described that, if successful, would result in a release of LNG, natural gas, or other flammable fluid from the terminal or tank ship operations. Each event sequence was described, including a number of the obstacles that would have to be overcome in order for a release to occur.

The specific question of whether an LNG import terminal is an attractive target for terrorists is beyond the scope of this study. A discussion of that issue would focus on whether a large-scale release of flammable fluid would satisfy one or more of the following criteria.

- Does the LNG import terminal serve as an iconic symbol, worthy of political impact?
- Does damage to the LNG import terminal result in a significant economic impact?
- Do the hazards associated with large releases from the LNG import terminal result in large loss of life or injuries to the public?

This study was designed to answer the third question.

Following the development of the LNG, natural gas, and other flammable fuel release sequences, the probability or frequency of each event was calculated. For the accidental releases, historical data from published sources containing LNG-specific or similar industry data were used when available. In the absence of such failure rate data, data from standard hydrocarbon operations were used.

The data for LNG tank ships show that there has never been a significant release of LNG from the LNG cargo tanks due to a collision with another ship or collision with a fixed object (such as a breakwater). Using the available data on LNG ship transits and assuming that the next collision with a fixed object or large ship results in a large release of LNG from one or more LNG cargo tanks, a release frequency of $1.25 \times (10)^{-5}$ per port call can be estimated. This results in a frequency of once in 80,000 port calls.

An evaluation of the probability of a successful terrorist-induced event in a flammable fuel or toxic chemical facility that would have similar or larger impacts than those associated with the proposed LNG terminal developed three critical points:

- Following the terrorist events of September 11, 2001, the United States General Accounting Office released a report stating that flammable fuels facilities do not present an attractive terrorist target compared to facilities that contain toxic materials. This is a direct result of the potential impacts of flammable fuels facilities being smaller than those associated with toxic chemical facilities.

- Data from the United States Environmental Protection Agency's Risk Management Plan Program show that 12,711 toxic and flammable fuel facilities in the United States have a potential public impact as large or larger than the proposed LNG terminal in the POLB. Using the first World Trade Center bombing (February, 1993) as a starting point for successful terrorist acts in the United States, provides an eleven-year period for developing a frequency. Recognizing that no successful terrorist event has been carried out against any of the 12,711 toxic or flammable fuel facilities in the United States, means that if one were to occur tomorrow, the frequency of such an event would be $7.15(10)^{-5}$/yr , or once in 140,000 years.

- The multi-layer security systems designed for the proposed LNG terminal operations are expected to hinder access to the Port of Long Beach, LNG terminal grounds, and Long Beach Harbor. These security systems would not and can not make the probability of an intentional act zero, but they can be assumed to reduce the potential success of such an act.

7.3 Consequence Analysis for Worst-Case Releases

The largest releases due to accidental causes were defined in a straight-forward manner, and only two required assumptions.

- The earthquake failure scenario is assumed to result in a catastrophic failure of one or both LNG storage tanks. The actual size of the hole is not critical to the analysis as long as it is large enough that the liquid can be released in a reasonably short period of time.

- A collision between an LNG tank ship and another ship of sufficient size and speed was assumed to result in a hole in outer hull, inner hull and one membrane cargo tank. If the release caused the subsequent failure of one or more membrane tanks, the release area in each subsequently affected tank was assumed to be represented by a similar sized hole.

The largest releases due to terrorist-induced failures were evaluated based on an analysis of a range of possible initiating events. Although an exact assessment of each event cannot be realized in a body of work such as this (e.g., exactly where would the truck bomb be parked?), the events evaluated represent a reasonable range of possible scenarios and impacts. The results of the analysis identifies the following events as those producing the largest releases from the LNG terminal and LNG tank ship operations.

LNG terminal land-based releases

- Truck bomb beside LNG storage tank resulting in hole in one LNG storage tank.
- Boeing 767 crashing into LNG storage tank resulting in hole in one LNG storage tank.

LNG tank ship releases

- Boeing 767 crashing into LNG tank ship resulting in holes in two LNG membrane cargo tanks.
- Boat bomb beside LNG tank ship resulting in a hole in one LNG membrane cargo tank.

Several consequence models were used to determine the size of the radiant energy and explosive overpressure hazard zones following the release and ignition of a flammable fluid from the LNG terminal or LNG tank ships described in this work. In some cases, a model was modified to perform in an alternate manner than it was originally designed for. The models used in the analysis are:

FERC's LNG spill onto water model
LNGFIRE3
DEGADIS
CANARY by Quest

The maximum distances to hazard levels defined for this work for the seven largest releases described above are presented in Table 7-1.

When considering intentional releases, the device that is used to effect the release of LNG, natural gas, or other hydrocarbons often involves an explosive or is itself a significant ignition source. In many of these cases, there is no opportunity for an evolving vapor/air flammable mixture to avoid an immediate and sustained ignition source. Thus, many of these releases always result in a pool fire, torch fire, or both. This is represented by the DNA (does not apply) notations in Table 7-1.

7.3.1 Flammable Cloud Travel Distances

Only three of the seven largest release scenarios have the potential to generate a drifting flammable vapor cloud following the release of LNG.

- The failure of both LNG storage tanks due to an earthquake.
- The release from an LNG tank ship following a collision with another ship.
- The release from an LNG tank ship following a collision with the breakwater.

Of these three, only the release from an LNG tank ship following a collision with another ship might be developed as a terrorist-induced event, provided the terrorists are able to commandeer a ship of sufficient size to ram an LNG tank ship hard enough to rupture one or more cargo tanks.

Table 7-1
Largest Consequence Analysis Results
Facility = LNG Import Terminal at Port of Long Beach, California

Cause of Release (A) = Accidental (I) = Intentional		Distance (ft) to 1,600 Btu/(hr·ft^2) Radiant Flux Level	Measured From	Distance (ft) to 1 psig Overpressure	Distance (ft) to LFL
(A)	Release from LNG storage tanks following earthquake	8,610	Center of LNG Pool on Water	NA	36,400
(A) (I)	Release from LNG tank ship following collision (outside breakwater) - 5 tanks fail	3,370	Center of LNG Pool on Water	NA	21,200
(A)	Release from LNG tank ship following collision with breakwater - 5 tanks fail	3,345	Center of LNG Pool by Tank Ship	NA	19,330
(I)	Release from LNG storage tank after truck bomb	7,020	Center of LNG Pool on Water	DNA	DNA
(I)	Release from LNG storage tank after plane crash	2,835	Center of LNG Pool on Water	DNA	DNA
(I)	Release from LNG tank ship after plane crash - 5 tanks fail	3,635	Center of LNG Pool by Tank Ship	DNA	DNA
(I)	Release from LNG tank ship after boat bomb - 5 tanks fail	3,320	Center of LNG Pool by Tank Ship	DNA	DNA

NA = Explosion overpressure level not achieved
DNA = Does not apply – vapor cloud formation is not possible following initiating event

It is extremely unlikely that an earthquake of the magnitude necessary to cause the failure of both LNG tanks would not create multiple immediate ignition sources for the ignition of any of the flammable vapors released in the terminal. There are no credible arguments that would allow for a flammable cloud of this size to exist in the immediate neighborhood of multiple ignition sources caused by such a massive earthquake. However, in the context of this worst-case analysis study, the flammable vapor cloud travel defined by this case – over water without any portion of the cloud traveling inland – may be defined as possible although it certainly is not credible.

Following an LNG tank ship collision with a breakwater or another ship, there is a reasonable chance that a release of LNG may result in a drifting cloud. The generation of a flammable cloud over an open water surface, void of immediate ignition sources, results in scenarios where the flammable portion of the cloud could drift some distance before encountering an ignition source. The most likely location of such an available ignition source would be near the shoreline.

Under the worst-case conditions defined for this work, the following cloud travel distances (and times) were calculated.

LNG Tank Ship Collision with Breakwater Scenarios	Maximum Distance to Lower Flammable Limit	Cloud Travel Time to Maximum Travel Distance
One cargo tank failure	9,260 ft (1.75 miles)	45 minutes
Sequential failure of five cargo tanks	19,330 ft (3.66 miles)	90 minutes

It should be kept in mind that these cloud travel distances can only be achieved it the drifting cloud remains over water. Once the cloud begins to travel inland, it is bound to encounter any one of many possible ignition sources. Once ignited, the flame will burn back toward the source and the ability of the cloud to drift further will have been halted. Therefore, it would be incorrect to develop flammable vapor cloud vulnerability zones (circles) for the following releases.

- Earthquake caused failures of both LNG storage tanks
- Collision of LNG tank ship with breakwater
- Collision of LNG tank ship with another ship

The areas along the shoreline that could be affected by a flash fire following the development of drifting flammable cloud are those areas without potential ignition sources (e.g., open beaches, parks, etc.). Once one or more ignition sources are encountered, the ingress of the cloud will be stopped.

7.3.2 Vapor Cloud Explosion Hazard Distances

Within an industrial area, large flammable vapor clouds are likely to be ignited before they reach a confined or congested area. If the leading edge of a large flammable cloud were to encounter a congested area, fill it with flammable vapor, and then find an ignition source, the overpressure impact would be a function of the volume of the congested area.

Without site-specific knowledge of each possible congested or obstructed area along the shoreline that could be reached by a drifting vapor cloud, it is impossible to calculate site-specific effects. However, the Baker-

Strehlow model does provide information on the maximum overpressure levels that could be achieved by natural gas explosions under a variety of conditions.

For flammable natural gas mixtures in outdoor residential or commercial areas that have some degree of obstruction (e.g., parked cars), the maximum overpressure generated in the cloud would be approximately 1.09 psig. This would be the localized overpressure in the congested area and the magnitude of the over-pressure will drop dramatically as distance from the congested area increases.

Using this information as a guide, the footprint of any overpressure map onto the shoreline near the LNG terminal will extend no further than the existing or created ignition sources nearest to the shoreline.

7.3.3 LNG Pool Fire Radiant Hazard Distances

For each accidental and intentional release listed in Table 7-1, there is a strong possibility that the vapor released (either directly, such as a natural gas release, or indirectly, such as vapors evolving off a liquid pool) will be ignited at the time of the release or shortly thereafter. The ignition source may be accidental in nature or intentional (as in the case of explosive devices). For the releases listed in Table 7-1 the dominant fire is due to fire above an expanding pool of LNG.

Since several of the potential releases involve LNG pools that may move away from the release point before they are ignited, or while they are ignited, the center of each fire is also identified in Table 7-1. When defining the extent of the 1,600 Btu/(hr·ft^2) vulnerability zone [second degree skin burns] for each release, the center of the fire should be used as the reference point.

7.4 <u>Potential Impact to Neighboring Facilities</u>

The proposed LNG import terminal is located on the west side and south end of Pier T in the Port of Long Beach. One task defined for this work was to calculate the potential impacts to neighboring industrial facilities, both current and proposed. These impacts were calculated for the worst-case events, both accidental and intentional.

As shown in Section 4, the large scale fires evaluated under worst-case atmospheric conditions have the potential to affect people in areas outside the LNG terminal fence line. When evaluating a person's possible exposure to a 1,600 Btu/(hr·ft^2) [second degree skin burns] radiant flux level, the use of vulnerability zones was employed to identify the total area that, under some circumstances, could be exposed to a radiant level greater than or equal to 1,600 Btu/(hr·ft^2). The same type of approach can be used to identify the potential radiant impact to the industrial areas neighboring the LNG terminal. For the purposes of this study, the radiant endpoint selected for evaluation was 10,000 Btu/(hr·ft^2), a level that would cause damage to structural steel.

As can be seen from Table 7-2, all of the largest events that occur at the terminal or the dock have the potential to impact the existing oil berth (T-121, which is 1,300 ft from a point centered between the two LNG storage tanks) and the proposed berth (T-124, which will be 750 ft from a point centered between the two LNG storage tanks). Several of the largest events have the potential to expose portions of T-124 and T-121 to radiant flux levels in excess of 10,000 Btu/(hr·ft^2). If this were to occur, flammable structures on T-124 and T-121 would be expected to ignite and ordinary storage tanks might incur a roof failure due to metal fatigue. Following a roof failure, the contents in the tank may ignite, resulting in a separate independent fire

Table 7-2
Largest Consequence Analysis Results – Equipment Impact
Facility = LNG Import Terminal at Port of Long Beach, California

Cause of Release (A) = Accidental (I) = Intentional		Distance (ft) to 10,000 Btu/(hr·ft^2) Radiant Flux Level	Measured From	Maximum Overpressure Achieved	Distance (ft) to 2.3 psig
(A)	Release from LNG storage tanks following earthquake	3,780	Center of LNG Pool on Water	1.09	NA
(I)	Release from LNG storage tank after truck bomb	3,090	Center of LNG Pool on Water	DNA	DNA
(I)	Release from LNG storage tank after plane crash	1,265	Center of LNG Pool on Water	DNA	DNA
(I)	Release from LNG tank ship after plane crash - 5 tanks fail	1,650	Center of LNG Pool by Tank Ship	DNA	DNA
(I)	Release from LNG tank ship after boat bomb - 5 tanks fail	1,635	Center of LNG Pool by Tank Ship	DNA	DNA

NA = Explosion overpressure level not achieved
DNA = Does not apply – vapor cloud formation is not possible following initiating event

source. The storage tanks on T-124 and T-121 are small in comparison to the size of the LNG fire being evaluated. The storage tanks would burn for a longer duration than the LNG fires, but would have significantly smaller impact on the surroundings.

The largest 10,000 Btu/(hr·ft^2) radiant vulnerability zone follows an earthquake-induced failure of both LNG storage tanks. The vulnerability zone for this pool fire is presented in Figure 7-1. A review of Figure 7-1 shows that this event can affect both T-121 and T-124, as well as portions of the POLB, but the 10,000 Btu/(hr·ft^2) vulnerability zone does not extend past the POLB boundary in any direction.

7.5 Comparison to Other Flammable Fuels Facilities

The potential worst-case impacts associated with the proposed LNG import terminal in the Port of Long Beach were compared to the potential worst-case impacts of three flammable fuel facilities. It should be noted that terrorist-induced failures were explicitly considered in only one of the three previous studies. However, as was the case when evaluating several of the events in the LNG import terminal, several of the events evaluated in the other flammable fuel facilities would have the same impact whether the initial release was accidental or intentional in nature.

The three flammable fuel facilities can be briefly described as follows.

Facility #1 The largest refrigerated propane terminal in northen California. This terminal has refrigerated propane storage tanks, pressurized ambient temperature storage tanks (bullets), and both railcar and tank truck loading.

Facility #2 Several petroleum product tank farms, located in southern California, with large capacity storage tanks containing a variety of petroleum products.

Facility #3 10 million tons per annum (10 mtpa) LNG import terminal in Mexico. This terminal will have a peak natural gas generation capacity of 2.4 billion cubic feet per day (2.4 bcfd).

None of the three facilities stores or processes any significant amount of toxic material. Thus, the comparison of potential hazards between the three facilities and the LNG import terminal is based solely on the flammable nature of the hydrocarbons processed and stored in each.

Each of the three flammable fuels fatalities evaluated has the potential to generate offsite impacts if a significant release of one or more of the fuels stored or processed in the facility were to be released. In each facility where an intentional release was evaluated, the impacts resulting from an intentional release were no larger than the impacts associated with one or more releases that could occur accidentally.

As can be seen from a review of Table 7-3, all four facilities have the potential to produce off-site impacts. The common misconception that explosions in flammable fuel facilities produce significant off-site explosion impacts is not supported by the modeling performed in this study, nor the historical record.

Additional hazard calculations were made for a range of LPG storage and transport vessels commonly found in the Long Beach areas. LPG vessels as small as 5 gallon (bar-b-que bottles) to refinery LPG storage spheres (12,500 barrels) were evaluated. Boiling Liquid Expanding Vapor Explosion (BLEVE) calculations were performed for the range of vessels identified, and the distances from the failed vessel to where second-degree skin burns might occur were defined. These distances ranged from 20 feet (for the bar-b-que bottle) to over 3,000 feet for the refinery storage sphere. The analysis was performed to provide easily recognizable examples of potential flammable fuel hazards in the Long Beach area.

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Table 7-3
Comparison of Worst-Case Impacts from Four Flammable Fuel Facilities

Facility	**Offsite Impacts and Maximum Hazard Impact Distance**		
	Radiant Heat (1,600 Btu/(hr·ft^2))	**Flash Fire (LFL)**	**Overpressure (1 psig)**
LNG Import Terminal, Long Beach, California	Yes max. distance = 8,610 ft	Yes max. distance = 34,600 ft	Yes max. distance = 320 ft
Propane Terminal, Northern California	Yes max. distance = 1,900 ft	Yes max. distance = 26,750 ft	Yes max. distance = 525 ft
Bulk Storage Terminals, Southern California	Yes max. distance = 595 ft	Yes max. distance = 675 ft	No
LNG Import Terminal, East Coast of Mexico	Yes max. distance = 1,240 ft	Yes max. distance = 21,200 ft	Yes max. distance = 200 ft

7.6 Summary

This study evaluated the extent of fire radiation and explosion overpressure hazards for a range of worst-case releases that included both accidental and intentional releases of flammable fluid from SES's proposed LNG terminal and tank ship operations in the POLB. The hazards associated with the proposed LNG import terminal and LNG tank ship operations are common to most flammable fuel facilities world-wide.

The historical record shows that successful intentional releases of flammable fuel from US facilities events have not occurred. This finding is supported by Federal reports addressing this topic that were written <u>after</u> the terrorist events of September 11, 2001. The Federal reports do not identify flammable fuel facilities as those that could affect large numbers of the public.

A full range of accidental and intentional releases of LNG, natural gas, and other flammable fluids were evaluated in order to quantify the potential impact if such releases were to occur. The accidental releases covered a range of credible events that could occur in an LNG terminal. The intentional releases covered a range of possible terrorist-induced releases ranging from localized damage to equipment as a result of a small explosive charge to more sophisticated and logistically challenging operations involving hijacked aircraft or ships.

The evaluation of the accidental and intentional release scenarios found that the most likely hazard to result from any of the releases is exposure to radiant heat from a pool fire or torch fire. The potential for any of the releases to produce damaging overpressures was found to be small and localized. The potential for drifting flammable vapor clouds to travel a significant distance before being ignited was small, with the possible exception of those releases that may occur outside of the Long Beach Harbor breakwater.

A review of the accidental and intentional events evaluated in this study finds that the events can be divided into four classes. These classes are defined by the event's historical record, or in the case of an earthquake capable of failing the LNG tanks, the predicted frequency of a such an earthquake. The four classes are presented in Table 7-4. In general, the historical record of the LNG import/export industry identifies significant failures within the process area to be the most likely event of those evaluated in this work. The second class involves an accidental release from an LNG tank ship. Although the historical record for LNG

Table 7-4
Comparison of Classes of LNG Release Events

Release Event	Estimate of Frequency of Event	Chance of Event
Rupture of process equipment within LNG terminal (accidental). – Rupture of process equipment - location A * – Rupture of process equipment - location B * – Rupture of process equipment - location C * – Rupture of process equipment - location D * – Rupture of process equipment - location E * – Release from process equipment - location F * – Release from process equipment - location G *	~$3(10)^{-3}$ per year [Historical record of all export and import LNG terminals worldwide.]	3 chances in 1000 per year [Note: all releases were in export terminals.]
LNG ship collision with another ship or breakwater within POLB or harbor entrance (accidental). – Release from LNG tank ship following collision with the breakwater - 1 tank fails – Release from LNG tank ship following collision with the breakwater - 5 tanks fail – Release from LNG tank ship following collision (outside breakwater) with another ship of sufficient size and speed - 1 tank fails – Release from LNG tank ship following collision (outside breakwater) with another ship of sufficient size and speed - 5 tanks fail	~ $1(10)^{-5}$ per port call [Historical record for LNG shipping. No loss of LNG has occurred.]	1 chance in 1000 per year [Assumes 100 LNG ship deliveries per year.]

* Details have been removed because this is considered to be Critical Energy Infrastructure Information (CEII) by the FERC.

Table 7-4
Comparison of Classes of LNG Release Events
(Continued)

Release Event	Estimate of Frequency of Event	Chance of Event
Earthquake-induced failure of LNG tank (accidental).	~$5(10)^{-5}$ per year [Project evaluation of tank design and local conditions.]	5 chances in 100,000 per year.
Release of LNG from terminal or ship due to intentional causes. – Terrorist-hijacked airplane crashing into one or both LNG tanks – Terrorist detonates truck bomb near an LNG tank – Terrorist fires rocket-propelled grenade (RPG) into one or both LNG tanks – Terrorist-hijacked airplane crashing into an LNG tank ship – Terrorist place boat bomb beside an LNG tank ship – Terrorist fires rocket-propelled grenade (RPG) into LNG tank ship – Terrorist-controlled ship collides with an LNG tank ship	~$7(10)^{-6}$ per year [Historical record of terrorist activities in US.]	7 chances in 1,000,000 per year. [Assumes LNG terminal is as valid a “target” as previous terrorist targets.]

tank ships does contain collisions, there has not been a release of LNG during or following a collision. Thus, the probability listed in Table 7-4 assumes that the next shipment of LNG ends in a collision and loss of cargo. As LNG shipments continue without incident, this frequency only gets smaller.

As described in the project documents, an earthquake capable of failing the full containment LNG tank designed for the site is "completely unrealistic." However, according to the analysis, it is not impossible. The frequency of such an earthquake is identified in Table 7-4. As described earlier, it should be kept in mind that an earthquake of sufficient magnitude to fail the LNG tanks would level the Long Beach area.

The last class of release events are those associated with intentional acts against the LNG terminal or LNG tank ship. These event frequencies are based on the historical record of terrorist events in the United States and are not specific to LNG terminals. This historical record of terrorist-induced events in the United States produces a frequency that is lower than the other event frequencies identified in this work.

The potential impact to neighboring POLB facilities was evaluated for the worst-case releases identified in this study. As would be expected in any analysis of this type, the industrial neighbors of the proposed LNG import terminal could be exposed to radiant hazards following events of the magnitude evaluated in this study. For the largest release studied, both accidental and intentional, there is the potential for the 10,000 Btu/(hr·ft^2) radiant flux level to extend 3,780 ft from the terminal. The areas within the POLB that could be affected by this release can be identified in Figure 7-1. It should be noted that the 10,000 Btu/(hr·ft^2) [structural steel damage] radiant level does not extend outside the POLB boundary for any scenario evaluated.

The potential hazards associated with accidental and intentional releases from the proposed LNG import terminal were compared to three other large flammable fuel facilities. Fire radiation impacts (pool fires and torch fires) provided the best method for comparing the impacts among the facilities. When this comparison is made, the maximum radiant impacts from the four facilities range from 595 to 8,610 feet from the fire source. In all four facilities, these worst-case radiant impacts, as defined by 1,600 Btu/(hr·ft^2) radiant heat flux [second degree burns], have the potential to extend past the facility property line.

Additional calculations for a range of LPG storage and transportation vessels in common use in the Long Beach area were made. The radiant zones were found to range from 20 to over 3,000 feet, dependent on the capacity of the vessel. These potential hazards exist in Long Beach on a day-to-day basis.

In the specific case of the proposed LNG import terminal in the Port of Long Beach, only two of the events evaluated have the potential to produce radiant impacts that could affect the public outside of the industrial area defined by the POLB boundary line. The largest radiant impact (as defined by 1,600 Btu/(hr·ft^2)) distance, was 8,610 ft, which would result from an earthquake of sufficient magnitude to fail both LNG storage tanks and the security wall surrounding the tanks. This failure allows a significant portion of the LNG to reach the water. Following ignition, the fire column (as defined by the FERC fire model) can produce 1,600 Btu/(hr·ft^2) slightly past the eastern POLB boundary line. The vulnerability zone for this scenario is presented in Figure 7-2 When reviewing this scenario, four things should be kept in mind.

1. An earthquake of the magnitude necessary to fail one or both tanks has been defined as "unrealistic" following a site-specific study. Thus, a catastrophic tank failure due to an earthquake should not be thought of as likely or probable. This accidental event, although defined as credible, would not normally be used as a benchmark for siting calculations.

2. An earthquake of the magnitude necessary to fail the full containment LNG storage tanks would be sufficient to level essentially every structure in the Port of Long Beach, as well as in the City of Long Beach.

3. In addition to the earthquake, a high wind would have to be blowing from the west to the east in order for the fire to impact the area outside the POLB boundary indicated in Figure 7-2.

4. The FERC fire model employed to make this calculation is not able to account for the lack of oxygen available to the core of such a large fire. Thus, the model overestimates the height and surface flux of the flame. This results in overestimating the potential impacts.

The second fire event that has the ability to produce 1,600 Btu/(hr$\cdot$ft^2) impacts past the POLB boundary is a pool fire following a truck bomb that fails one of the LNG storage tanks as well as the security wall. This event, although intentional in nature, results in a fire similar to, but smaller than, the fire associated with the earthquake (Figure 7-3). In this case, the 1,600 Btu/(hr$\cdot$ft^2) impact zone does not extend as far as the earthquake-induced failure since the LNG inventory is less (only one tank fails). However, issues 2 and 3 listed above would also apply to this scenario.

All the remaining LNG fire events evaluated for this study (those associated with terminal operations, storage, and LNG tank ship movements and operations) have no fire radiation impacts that extend past the POLB boundary. This is true whether the initiating event is accidental or intentional.

In conclusion, the results of this study can be summarized by the following points.

- The historical record and the Federal government's evaluation of flammable fuel facilities does not support the contention that the proposed LNG terminal would make an attractive terrorist target.

- If a successful terrorist-induced event occurred tomorrow in <u>any</u> toxic chemical or flammable fuels facility in the United States that could impact as many or more people than the proposed LNG import terminal in the POLB, the historical frequency would then be approximately 7.15 x $(10)^{-6}$/yr.

- The fire radiation hazards from LNG pool fires are the most likely hazards to occur, and they produce the largest hazard zones should they occur. Significant overpressures covering a large area are not possible and the opportunity for drifting flammable vapor clouds to travel any significant distance over land before igniting is not credible.

- None of the accidental or intentional releases from the LNG terminal or LNG tank ship operations have the ability to produce radiant levels (10,000 Btu/(hr$\cdot$ft^2)) capable of damaging industrial equipment outside the POLB boundary.

- Only one accidental release (that caused by an earthquake of sufficient magnitude to fail the LNG tanks) can produce a radiant hazard (1,600 Btu/(hr$\cdot$ft^2); second degree skin burns) to persons outside of the POLB boundary. It should be recognized that an earthquake of this magnitude would, on its own, cause wide-spread destruction in the POLB and Long Beach.

- Only one intentional release, the effective placement of a truck bomb beside one of the LNG storage tanks, can produce a radiant hazard (1,600 Btu/(hr$\cdot$ft^2); second degree skin burns) to persons outside of the POLB boundary, and only under specific atmospheric conditions.

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Public access for the above information is available only through the Public Reference Room, or by e-mail at public.referenceroom@ferc.gov

SECTION 8
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APPENDIX A
FAILURE RATE DATA REFERENCES

Failure Rate Data References

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Gaskets	*Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants.* [USNRC, 1975] *Reliability Technology* [Green and Bourne, 1972]
Valves	*Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants.* [USNRC, 1975] *Guidelines for Process Equipment Reliability Data, with Data Tables* [CCPS, 1989b]
Pressure Vessels	*Guidelines for Process Equipment Reliability Data, with Data Tables* [CCPS, 1989b] "Pressure Vessel Reliability." *Journal of Pressure Vessel Technology* [Bush, 1975] *A Survey of Defects in Pressure Vessels in the United Kingdom for the Period 1962-1978 and Its Relevance to Nuclear Primary Circuits* [Smith and Warwick, 1981] *1997 Economic Census, Transportation, 1997 Commodity Flow Survey* [USCB, 1999] *Major Hazard Aspects of the Transport of Dangerous Substances* [HSE, 1991] *LPG, A Study* [TNO, 1983] "Estimation of Cold Failure Frequency of LPG Tanks in Europe" [Sooby and Tolchard, 1993]
Pumps	*Reliability Technology* [Green and Bourne, 1972] *OREDA, Offshore Reliability Data Handbook* (First Edition) [OREDA, 1984] *Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants.* [USNRC, 1975] *Guidelines for Process Equipment Reliability Data, with Data Tables* [CCPS, 1989b]
Transfer Hoses	*Reliability Technology* [Green and Bourne, 1972] *Accident Facts, 1997 Edition* [Lees, 1996] *Guidelines for Process Equipment Reliability Data, with Data Tables* [CCPS, 1989b]
Storage Tanks	*Guidelines for Quantitative Risk Assessment* (First Edition) [TNO, 1999]

APPENDIX B
CANARY BY QUEST® MODEL DESCRIPTIONS

The following model descriptions are taken from the CANARY by Quest User Manual.

Section A	Engineering Properties
Section B	Pool Fire Radiation Model
Section C	Torch Fire and Flare Radiation Model
Section D	Fireball Model
Section E	Fluid Release Model
Section F	Momentum Jet Dispersion Model
Section G	Heavy Gas Dispersion Model
Section I	Vapor Cloud Explosion Model

Engineering Properties

Purpose

The purpose of this model is to provide an accurate means of computing physical and thermodynamic properties of a wide range of chemical mixtures and pure components using a minimum of initial information.

Required Data

(a) Fluid composition
(b) Temperature and pressure of the fluid prior to release

Methodology

Basic thermodynamic properties are computed using the Peng-Robinson equation of state [Peng and Robinson, 1976]. The necessary physical and thermodynamic properties are calculated in the following manner.

Step 1: The temperature and pressure of the fluid at storage conditions and the identity and mole fraction of each component of the fluid are obtained. Mixture parameters are determined using data from the extensive properties data base within CANARY.

Step 2: Each calculation begins with the computation of the vapor and liquid fluid composition. For cases where the temperature and pressure result in only one phase being present, the vapor or liquid composition will be the same as the initial feed composition. The composition calculation is an iterative procedure using a modification of the techniques described by Starling [1973].

Step 3: Once the vapor and liquid compositions are known, the vapor and liquid densities, enthalpies, entropies, and heat capacities can be computed directly. Other physical properties (viscosity, thermal conductivity, surface tension, etc.) are computed using correlations developed in Reid, Prausnitz, and Poling [1987].

Step 4: A matrix of properties is computed over a range of temperatures and pressures. Physical and thermodynamics properties required by other models within CANARY are then interpolated from this table.

Basic Thermodynamic Equations

$$Z^3 - (1 - B) \cdot Z^2 + \left(A - 3 \cdot B^2 - 2 \cdot B\right) \cdot Z - \left(A \cdot B - B^2 - B^3\right) = 0 \tag{1}$$

where: Z = fluid compressibility factor, $\frac{P \cdot V}{R \cdot T}$, dimensionless

P = system pressure, kPa
V = fluid specific volume, m^3/kmol

R = gas constant, 8.314 $m^3 \cdot$ kPa/(kmol$\cdot$K)
T = absolute temperature, K

$$A = \frac{a \cdot P}{R^2 \cdot T^2}$$

$$a = 0.45724 \cdot \frac{R^2 \cdot T^2}{P_c} \cdot \alpha$$

$$\alpha = \left[1 + m \cdot \left(1 - T_r^{0.5}\right)^2\right]$$

$$m = 0.37464 + 1.54226 \cdot \omega - 0.26992 \cdot \omega^2$$

ω = acentric factor

$$T_r = \frac{T}{T_c}$$

T_c = pseudo-critical temperature, K
P_c = pseudo-critical pressure, kPa

$$B = \frac{b \cdot P}{R \cdot T}$$

$$b = 0.0778 \cdot R \cdot \frac{T_c}{P_c}$$

$$H = H^o + \frac{P}{\rho} - R \cdot T + \int_0^{\rho} \left[P - T \cdot \left(\frac{\partial P}{\partial T}\right)_{\rho}\right] \cdot \left(\frac{d\rho}{\rho^2}\right) \tag{2}$$

where: H = enthalpy of fluid at system conditions, kJ/kg
H^o = enthalpy of ideal gas at system temperature, kJ/kg

$$S = S^o - R \cdot \ln\left(\rho \cdot R \cdot T\right) + \int_0^{\rho} \left[\rho \cdot R - \left(\frac{\partial P}{\partial T}\right)_{\rho}\right] \cdot \left(\frac{d\rho}{\rho^2}\right) \tag{3}$$

where: S = entropy of fluid at system conditions, kJ/(kg$\cdot$K)
S^o = entropy of ideal gas at system temperature, kJ/(kg$\cdot$K)

$$R \cdot T \cdot \ln\left(\frac{f_i}{f_i^o}\right) = \left[\left(H_i - H_i^o\right) - T \cdot \left(S_i - S_i^o\right)\right] \tag{4}$$

where: f_i = fugacity of component i, kPa
f_i^o = standard state reference fugacity, kPa

References

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Reid, R. C., J. M. Prausnitz, and B. E. Poling, *The Properties of Gases and Liquids* (Fourth Edition). McGraw-Hill Book Company, New York, New York, 1987.

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Pool Fire Radiation Model

Purpose

The purpose of this model is to predict the impact of fire radiation emitted by flames that are fueled by vapors emanating from liquid pools. Specifically, the model predicts the maximum radiant heat flux incident upon a target as a function of distance between the target and the flame.

Required Data

(a) Composition of the liquid in the pool
(b) Temperature of the liquid in the pool
(c) Wind speed
(d) Air temperature
(e) Relative humidity
(f) Elevation of the target (relative to grade)
(g) Elevation of the pool (relative to grade)
(h) Dimensions of the free surface of the pool
(i) Orientation of the pool (relative to the wind direction)
(j) Spill surface (land or water)

Methodology

Step 1: The geometric shape of the flame is defined. The flame column above a circular pool, square pool, or rectangular pool is modeled as an elliptical cylinder.

Step 2: The dimensions of the flame column are determined. The dimensions of the base of the flame are defined by the pool dimensions. An empirical correlation developed by Thomas [1965] is used to calculate the length (height) of the flame.

$$L = 42 \cdot D_h \cdot \left(\frac{\dot{m}}{\rho_a \cdot \left(g \cdot D_h \right)^{0.5}} \right)^{0.61}$$

where:
L = length (height) of the flame, m
D_h = hydraulic diameter of the liquid pool, m
$\dot{m}$ = mass burning flux, kg/(m$^2\cdot$s)
ρ_a = density of air, kg/m^3
g = gravitational acceleration, 9.8 m/s^2

Notes: Mass burning fluxes used in the Thomas equation are the steady-state rates for pools on land (soil, concrete, etc.) or water, whichever is specified by the user.

For pool fires with hydraulic diameters greater than 100 m, the flare length, L, is set equal to the length calculated for $D_h = 100$ m.

Step 3: The angle (Φ) to which the flame is bent from vertical by the wind is calculated using an empirical correlation developed by Welker and Sliepcevich [1970].

$$\frac{\tan(\Phi)}{\cos(\Phi)} = 3.2 \cdot \left(\frac{D_h \cdot u \cdot \rho_a}{\mu_a}\right)^{0.07} \cdot \left(\frac{u^2}{g \cdot D_h}\right)^{0.7} \cdot \left(\frac{\rho_v}{\rho_a}\right)^{-0.6}$$

where: Φ = angle the flame tilts from vertical, degrees
u = wind speed, m/s
μ_a = viscosity of air, kg/(m·s)
ρ_v = density of fuel vapor, kg/m^3

Step 4: The increase in the downwind dimension of the base of the flame (flame drag) is calculated using a generalized form of the empirical correlation Moorhouse [1982] developed for large circular pool fires.

$$D_w = 1.5 \cdot D_x \cdot \left(\frac{u^2}{g \cdot D_x}\right)^{0.069}$$

where: D_w = downwind dimension of base of tilted flame, m
D_x = downwind dimension of the pool, m

Step 5: The flame is divided into two zones: a clear zone in which the flame is not obscured by smoke; and a smoky zone in which a fraction of the flame surface is obscured by smoke. The length of the clear zone is calculated by the following equation, which is based on an empirical correlation developed by Pritchard and Binding [1992].

$$L_c = 55.05 \cdot D_h^{-0.6} \cdot \left(\frac{\dot{m}}{\rho_a}\right)^{1.13} \cdot (u+1)^{0.179} \cdot \left(\frac{C}{H}\right)^{-2.49}$$

where: L_c = length of the clear zone, m
$\frac{C}{H}$ = carbon/hydrogen ratio of fuel, dimensionless

Step 6: The surface flux of the clear zone is calculated using the following equation.

$$q_{cz} = q_{sm} \cdot \left(1 - e^{-b \cdot D_h}\right)$$

where: q_{cz} = surface flux of the clear zone, kW/m^2
q_{sm} = maximum surface flux, kW/m^2
b = extinction coefficient, m^{-1}

Average surface flux of the smoky zone, q_{cz}, is then calculated, based on the following assumptions.

- The smoky zone consists of clean-burning areas and areas in which the flame is obscured by smoke.
- Within the smoky zone, the fraction of the flame surface that is obscured by smoke is a function of the fuel properties and pool diameter.
- Smoky areas within the smoky zone have a surface flux of 20 kW/m^2 [Hagglund and Persson,1976].
- Clean-burning areas of the smoky zone have the same surface flux as the clean-burning zone.
- The average surface flux of the smoky zone is the area-weighted average of the surface fluxes for the smoky areas and the clean-burning areas within the smoky zone.

(This two-zone concept is based on the Health and Safety Executive POOLFIRE6 model, as described by Rew and Hulbert [1996].)

Step 7: The surface of the flame is divided into numerous differential areas. The following equation is then used to calculate the view factor from a differential target, at a specific location outside the flame, to each differential area on the surface of the flame.

$$F_{dA_t \to dA_f} = \frac{\cos(\beta_t) \cdot \cos(\beta_f)}{\pi \cdot r^2} \cdot dA_f \qquad \text{for } [\ \beta_t\ ] \text{ and } [\ \beta_f\ ] < 90^\circ$$

where: $F_{dA_t \to dA_f}$ = view factor from a differential area on the target to a differential area on the surface of the flame, dimensionless
dA_f = differential area on the flame surface, m^2
dA_t = differential area on the target surface, m^2
r = distance between differential areas dA_t and dA_f, m
β_t = angle between normal to dA_t and the line from dA_t to dA_f, degrees
β_f = angle between normal to dA_f and the line from dA_t to dA_f, degrees

Step 8: The radiant heat flux incident upon the target is computed by multiplying the view factor for each differential area on the flame by the appropriate surface flux (q_{cz} or q_{sz}) and by the appropriate atmospheric transmittance, then summing these values over the surface of the flame.

$$q_{ai} = \sum_{A_f} q_{sf} \cdot F_{dA_t \to dA_f} \cdot \tau$$

where: q_{ai} = attenuated radiant heat flux incident upon the target due to radiant heat emitted by the flame, kW/m^2
A_f = area of the surface of the flame
q_{sf} = radiant heat flux emitted by the surface of the flame, kW/m^2 (q_{sf} equals either q_{cz} or q_{sz}, as appropriate)
τ = atmospheric transmittance, dimensionless

Atmospheric transmittance, τ, is a function of absolute humidity and r, the path length between differential areas on the flame and target [Wayne, 1991].

Step 9: Steps 7 and 8 are repeated for numerous target locations.

Validation

Several of the equations used in the Pool Fire Radiation Model are empirical relationships based on data from medium- to large-scale experiments, which ensures reasonably good agreement between model predictions and experimental data for variables such as flame length and tilt angle. Comparisons of experimental data and model predictions for incident heat flux at specific locations are more meaningful and of greater interest. Unfortunately, few reports on medium- or large-scale experiments contain the level of detail required to make such comparisons.

One source of detailed test data is a report by Welker and Cavin [1982]. It contains data from sixty-one pool fire tests involving commercial propane. Variables that were examined during these tests include pool size (2.7 to 152 m^2) and wind speed. Figure B-1 compares the predicted values of incident heat flux with experimental data from the sixty-one pool fire tests.

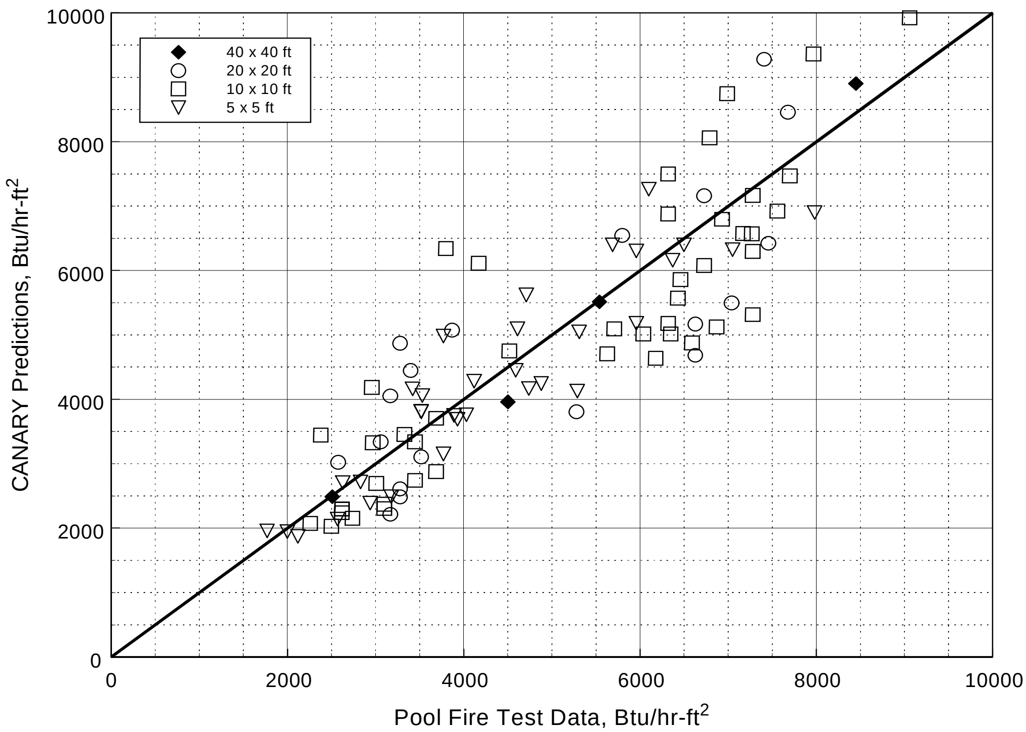

Figure B-1

In another series of tests, fire radiation measurements were taken for large liquefied natural gas (LNG) pool fires. The Montoir tests are the largest tests of LNG fires, involving pools up to 35 meters in diameter [Nédelka, Moorhouse, and Tucker, 1989]. Figure B-2 compares the radiation isopleths predicted by CANARY with the actual measurements taken in Test 2 of the Montoir series.

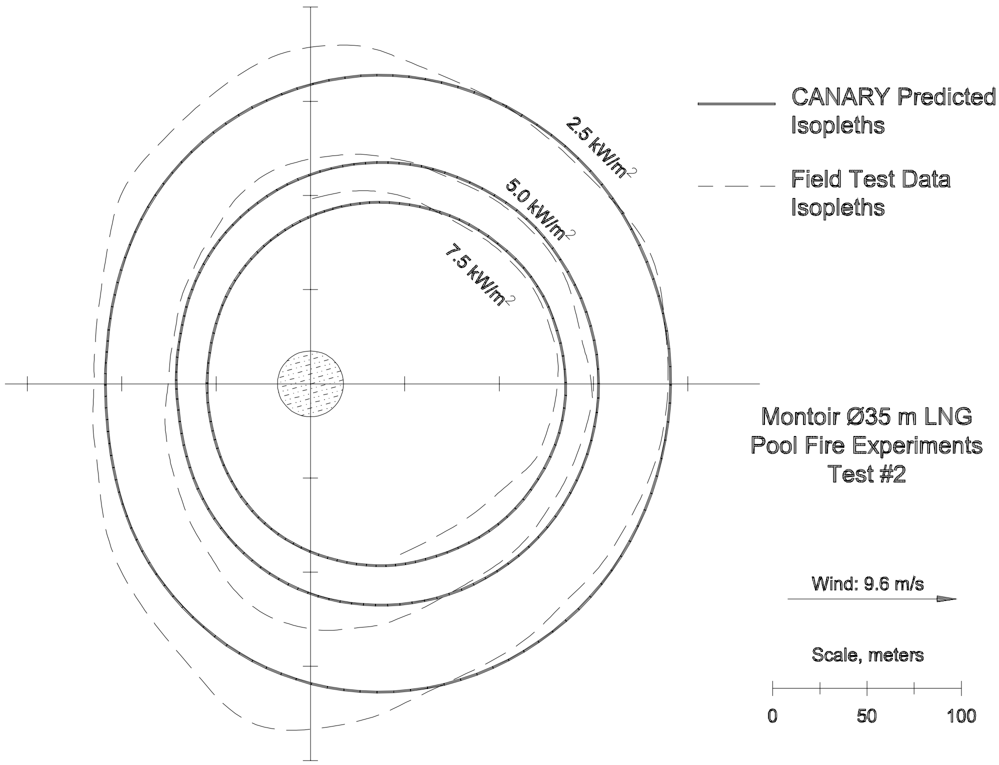

Figure B-2

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Torch Fire and Flare Radiation Model

Purpose

The purpose of this model is to predict the impact of fire radiation emitted by burning jets of vapor. Specifically, the model predicts the maximum radiant heat flux incident upon a target as a function of distance between the target and the point of release.

Required Data

(a) Composition of the released material
(b) Temperature and pressure of the material before release
(c) Mass flow rate of the material being released
(d) Diameter of the exit hole
(e) Wind speed
(f) Air temperature
(g) Relative humidity
(h) Elevation of the target (relative to grade)
(i) Elevation of the point of release (relative to grade)
(j) Angle of the release (relative to horizontal)

Methodology

Step 1: A correlation based on a Momentum Jet Model is used to determine the length of the flame. This correlation accounts for the effects of:

- composition of the released material,
- diameter of the exit hole,
- release rate,
- release velocity, and
- wind speed.

Step 2: To determine the behavior of the flame, the model uses a momentum-based approach that considers increasing plume buoyancy along the flame and the bending force of the wind. The following equations are used to determine the path of the centerline of the flame [Cook, et al., 1987].

$$\Phi_X = \left(\rho_{ja}\right)^{0.5} \cdot \bar{u} \cdot \sin(\theta) \cdot \cos(\varphi) + \left(\rho_\infty\right)^{0.5} \cdot u_\infty \qquad \text{(downwind)}$$

$$\Phi_Y = \left(\rho_{ja}\right)^{0.5} \cdot \bar{u} \cdot \sin(\theta) \cdot \sin(\varphi) \qquad \text{(crosswind)}$$

$$\Phi_Z = \left(\rho_{ja}\right)^{0.5} \cdot \bar{u} \cdot \cos(\theta) + \left(\rho_\infty\right)^{0.5} \cdot u_b \cdot \frac{(i+1)}{n} \qquad \text{(vertical)}$$

where: Φ_{XYZ} = momentum flux in X, Y, Z direction
ρ_{ja} = density of the jet fluid at ambient conditions, kg/m^3

$\bar{u}$ = average axial velocity of the flame, m/s
θ = release angle in $X-Z$ plane (relative to horizontal), degrees
φ = release angle in $X-Y$ plane (relative to downwind), degrees
ρ_∞ = density of air, kg/m^3
u_∞ = wind speed, m/s
ρ_b = density of combustion products, kg/m^3
u_b = buoyancy velocity, m/s
n = number of points taken along the flame length

These correlations were developed to predict the path of a torch flame when released at various orientations. The model currently does not allow a release angle in a crosswind direction; the release angle is confined to the downwind/vertical plane (i.e., $\varphi = 0$).

Step 3: The angle of flame tilt is defined as the inclination of a straight line between the point of release and the end point of the flame centerline path (as determined in Step 2).

Step 4: The geometric shape of the flame is defined as a frustum of a cone (as suggested by several flare/fire researchers [e.g., Kalghatgi, 1983, Chamberlain, 1987]), but modified by adding a hemisphere to the large end of the frustum. The small end of the frustum is positioned at the point of release, and the centerline of the frustum is inclined at the angle determined in Step 3.

Step 5: The surface emissive power is determined from the molecular weight and heat of combustion of the burning material, the release rate and velocity, and the surface area of the flame.

Step 6: The surface of the flame is divided into numerous differential areas. The following equation is then used to calculate the view factor from a differential target, at a specific location outside the flame, to each differential area on the surface of the flame.

$$F_{dA_t \rightarrow dA_f} = \frac{\cos(\beta_t) \cdot \cos(\beta_f)}{\pi \cdot r^2} \cdot dA_f \qquad \text{for } [\,\beta_t\,] \text{ and } [\,\beta_f\,] < 90$$

where: $F_{dA_t \rightarrow dA_f}$ = view factor from a differential area on the target to a differential area on the surface of the flame, dimensionless
dA_f = differential area on the flame surface, m^2
dA_t = differential area on the target surface, m^2
r = distance between differential areas dA_t and dA_f, m
β_t = angle between normal to dA_t and the line from dA_t to dA_f, degrees
β_f = angle between normal to dA_f and the line from dA_t to dA_f, degrees

Step 7: The radiant heat flux incident upon the target is computed by multiplying the view factor for each differential area on the flame by the surface missive power and by the appropriate atmospheric transmittance, then summing these values over the surface of the flame.

$$q_{ai} = \sum_{A_f} q_{sf} \cdot F_{dA_t \rightarrow dA_f} \cdot \tau$$

where: q_{ai} = attenuated radiant heat flux incident upon the target due to radiant heat emitted by the flame, kW/m^2
A_f = area of the surface of the flame
q_{sf} = radiant heat flux emitted by the surface of the flame, kW/m^2
τ = atmospheric transmittance, dimensionless

Atmospheric transmittance, τ, is a function of absolute humidity and r, the path length between differential areas on the flame and target [Wayne, 1991].

Step 8: Steps 6 and 7 are repeated for numerous target locations.

Validation

Several of the equations used in the Torch Fire and Flare Radiation Model are empirical relationships based on data from medium- to large-scale experiments, which ensures reasonably good agreement between model predictions and experimental data for variables such as flame tilt angle. Comparisons of experimental data and model predictions for incident heat flux at specific locations are more meaningful and of greater interest. Unfortunately, few reports on medium- or large-scale experiments contain the level of detail required to make such comparisons.

One reasonable source of test data is a report by Chamberlain [1987]. It contains data from seven flare tests involving natural gas releases from industrial flares, with several data points being reported for each test. Variables that were examined during these tests include release diameter (0.203 and 1.07 m), release rate and velocity, and wind speed. Figure C-1 compares the predicted values of incident heat flux with experimental data from the seven flare tests.

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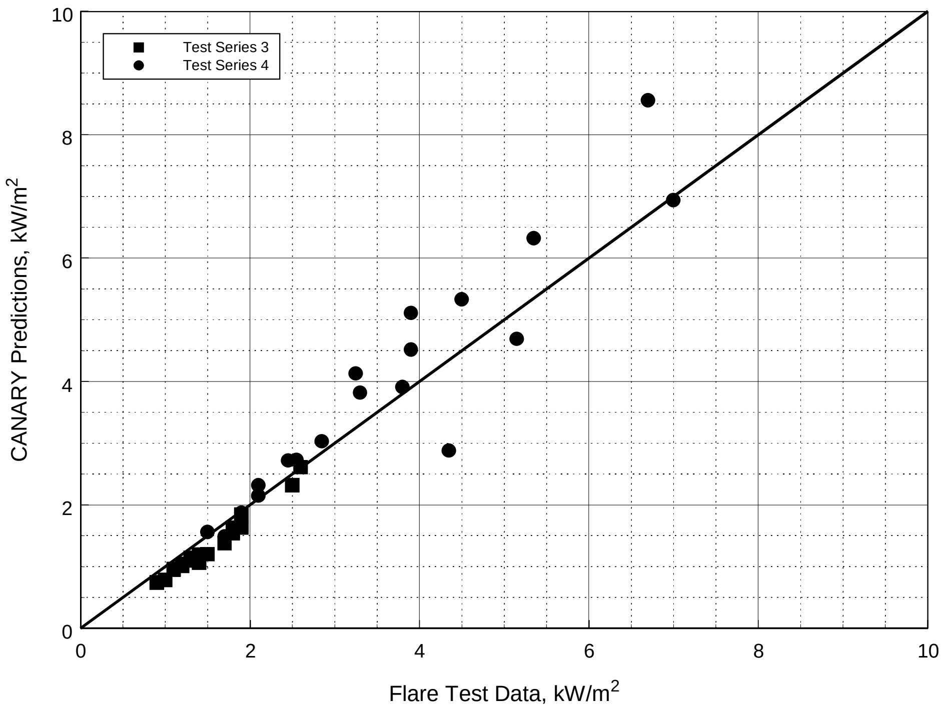
Test Series 3
Test Series 4
CANARY Predictions, kW/m2
Flare Test Data, kW/m2
0
2
4
6
8
10

Figure C-1

Fireball Model

Purpose

The purpose of the Fireball Model is to predict the impact of thermal radiation emitted by fireballs that result from catastrophic failures of pressure vessels containing superheated liquids. Specifically, the model predicts the average radiant heat flux incident upon a grade-level target as a function of the horizontal distance between the target and the center of the fireball.

Required Data

(a) Composition of flammable liquid within the pressure vessel
(b) Mass of flammable liquid within the pressure vessel
(c) Pressure within vessel just prior to rupture
(d) Temperature of the liquid within the vessel just prior to rupture
(e) Air temperature
(f) Relative humidity

Methodology

Step 1: Calculate the mass of fuel consumed in the fireball. The mass of fuel in the fireball is equal to the smaller of the mass of fuel in the vessel (as specified by the user), or three times the mass of fuel that flashes to vapor when it is released to the atmosphere [Hasegawa and Sato, 1977].

Step 2: Calculate the maximum diameter of the fireball using the empirical correlation from Roberts [1981/82].

$$D_{\max} = 5.8 \cdot M_f^{1/3}$$

where: $D_{\max}$ = maximum diameter of the fireball, m
M_f = mass of fuel in the fireball, kg

Step 3: Calculate fireball duration using the following empirical correlation [Martinsen and Marx, 1999].

$$t_d = 0.9 \cdot M_f^{1/4}$$

where: t_d = fireball duration, s
M_f = mass of fuel in the fireball, kg

Step 4: Calculate the size of the fireball and its location, as a function of time. The fireball is assumed to grow at a rate that is proportional to the cube root of time, reaching its maximum diameter, $D_{\max}$, at the time of liftoff, $t_d / 3$. During its growth phase, the fireball remains tangent to grade. After liftoff, it rises at a constant rate [Shield, 1994].

Step 5: Estimate the surface flux of the fireball. The fraction of the total available heat energy that is emitted as radiation is calculated using the equation derived by Roberts [1981/82].

$$f = 0.0296 \cdot P^{0.32}$$

where: f = fraction of available heat energy released as radiation, dimensionless
P = pressure in vessel at time of rupture, kPa

The total amount of energy emitted as radiation is then calculated.

$$E_r = f \cdot M_f \cdot \Delta H_c$$

where: E_r = energy emitted as radiation, kJ
ΔH_c = heat of combustion, kJ/kg

The surface flux is estimated by dividing E_r by the average surface area of the fireball and the fireball duration, but it is not allowed to exceed 400 kW/m^2.

Step 6: Calculate the maximum view factor from a differential target (at specific grade level locations outside the fireball) to the fireball, using the simple equation for a spherical radiator [Howell, 1982].

$$F = \frac{R^2}{H^2}$$

where: F = view factor from differential area to the fireball, dimensionless
R = radius of the fireball, m
H = distance between target and the center of the fireball, m

R and H vary with time due to the growth and rise of the fireball. Therefore, the duration of the fireball is divided into time intervals and a view factor is calculated at the end of each interval.

Step 7: Compute the attenuated radiant heat flux at each target location, at the end of each time interval, by multiplying the appropriate view factor by the surface flux of the fireball and by the appropriate atmospheric transmittance. The transmittance of the atmosphere is a function of the absolute humidity and path length from the fireball to the target [Wayne, 1991]. For each target location, calculate the average attenuated heat flux over the duration of the fireball.

Step 8: Calculate the absorbed energy at each target location. For a given location, the energy absorbed during each time interval is computed by multiplying the length of the interval by the average attenuated radiant heat flux for that interval. The absorbed energies for all time intervals are then summed to determine the radiant energy absorbed over the duration of the fireball.

Step 9: Calculate the integrated dosage at each target location. This is computed in the same manner as absorbed energy is computed in Step 8, except that the average attenuated radiant heat flux for each time interval is taken to the 4/3rds power before it is multiplied by the time interval. This allows the dosage to be used in the probit equation for fatalities from thermal radiation [Eisenberg, Lynch, and Breeding, 1975].

$$Pr = -38.4785 + 2.56 \cdot \ln\left(q^{4/3} \cdot t\right)$$

where: Pr = probit
q = radiant heat flux, W/m^2
t = exposure time, s

Validation

Several of the equations used in the Fireball Model are empirical relationships based on data from small- to medium-scale experiments, which ensures reasonably good agreement between model predictions and experimental data for variables such as maximum fireball diameter. Comparisons of experimental data and model predictions for average incident heat flux, absorbed energy, or dosage are more meaningful and of greater interest. Unfortunately, very few reports on small- or medium-scale fireball experiments contain the level of detail required to make such comparisons, and no such data are available for large-scale experiments.

One of the most complete sources of test data for medium-scale fireball tests is a report by Johnson, Pritchard, and Wickens [1990]. It contains data on five BLEVE tests that involved butane and propane, in quantities up to 2,000 kg. Figure D-1 compares the predicted values of absorbed energy with experimental data from those five BLEVE tests.

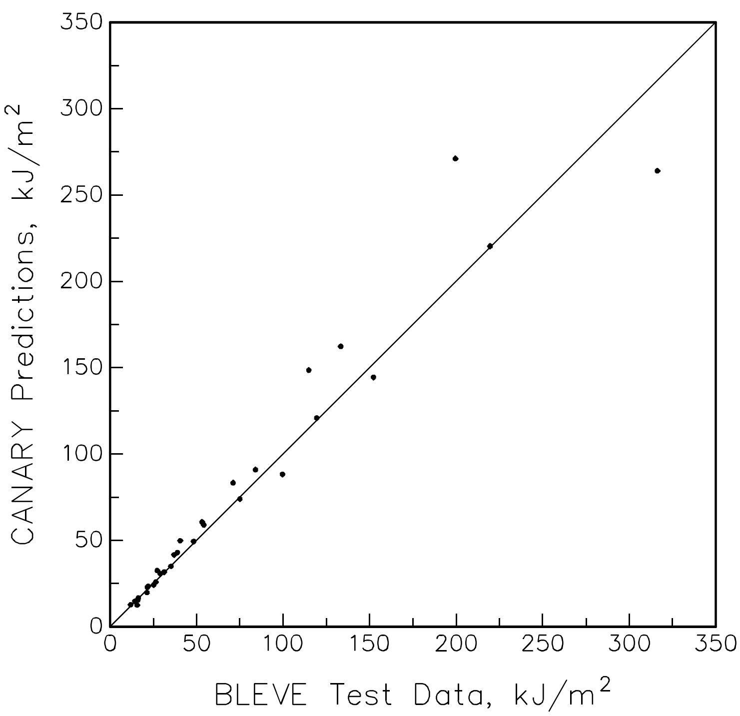

Figure D-1

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Fluid Release Model

Purpose

The purpose of the Fluid Release Model is to predict the rate of mass release from a breach of containment. Specifically, the model predicts the rate of flow and the physical state (liquid, two-phase, or gas) of the release of a fluid stream as it enters the atmosphere from a circular breach in a pipe or vessel wall. The model also computes the amount of vapor and aerosol produced and the rate at which liquid reaches the ground.

Required Data

(a) Composition of the fluid
(b) Temperature and pressure of the fluid just prior to the time of the breach
(c) Normal flow rate of fluid into the vessel or in the pipe
(d) Size of the pipe and/or vessel
(e) Length of pipe
(f) Area of the breach
(g) Angle of release relative to horizontal
(h) Elevation of release point above grade

Methodology

Step 1: Calculation of Initial Flow Conditions

The initial conditions (before the breach occurs) in the piping and/or vessel are determined from the input data, coupled with a calculation to determine the initial pressure profile in the piping. The pressure profile is computed by dividing the pipe into small incremental lengths and computing the flow conditions stepwise from the vessel to the breach point. As the flow conditions are computed, the time required for a sonic wave to traverse each section is also computed. The flow in any length increment can be all vapor, all liquid, or two-phase (this implies that the sonic velocity within each section may vary). As flow conditions are computed in each length increment, checks are made to determine if the fluid velocity has exceeded the sonic velocity or if the pressure in the flow increment has reached atmospheric. If either condition has been reached, an error code is generated and computations are stopped.

Step 2: Initial Unsteady State Flow Calculations

When a breach occurs in a system with piping, a disturbance in flow and pressure propagates from the breach point at the local sonic velocity of the fluid. During the time required for the disturbance to reach the upstream end of the piping, a period of highly unsteady flow occurs. The portion of the piping that has experienced the passage of the pressure disturbance is in accelerated flow, while the portion upstream of the disturbance is in the same flow regime as before the breach occurred.

To compute the flow rate from the breach during the initial unsteady flow period, a small time increment is selected and the distance that the pressure disturbance has moved in that time increment is computed using the sonic velocity profile found in the initial pressure profile calculation. The disturbed length is subdivided into small increments for use in an iterative pressure balance calculation. A pressure balance is achieved when a breach pressure is found that balances the flow from the breach and the flow in the disturbed section of piping. Another time increment is added, and the iterative procedure continues. The unsteady period continues until the pressure disturbance reaches the upstream end of the pipe.

Step 3: Long-Term Unsteady State Flow Calculations

The long-term unsteady state flow calculations are characterized by flow in the piping system that is changing more slowly than during the initial unsteady state calculations. The length of accelerated flow in the piping is constant, set by the user input pipe length. The vessel contents are being depleted, resulting in a potential lowering of pressure in the vessel. As with the other flow calculations, the time is incremented and the vessel conditions are computed. The new vessel conditions serve as input for the pressure drop calculations in the pipe. When a breach pressure is computed that balances the breach flow with the flow in the piping, a solution for that time is achieved. The solution continues until the ending time or other ending conditions are reached.

The frictional losses in the piping system are computed using the equation:

$$h = \left(\frac{4 \cdot f \cdot L \cdot U_{ls}^2}{2 \cdot g_c \cdot D_e} \right) \tag{1}$$

where: h = head (pressure) loss, ft of fluid
f = friction factor
L = length of system, ft
U = average flowing velocity, ft/sec
g_c = gravitational constant, 32.2 $lb_m \cdot ft/(lb_f \cdot sec^2)$
D_e = equivalent diameter of duct, ft

The friction factor is computed using the following equation:

$$\frac{1}{\sqrt{f}} = 1.74 - 2.0 \cdot \log_{10} \left[\frac{2 \cdot \varepsilon}{D_e} + \frac{18.7}{Re \cdot \sqrt{f}} \right] \tag{2}$$

where: ε = pipe roughness, ft
Re = Reynolds number, $D_e \cdot U \cdot \rho / \mu$, dimensionless
ρ = fluid density, lb/ft^3
μ = fluid viscosity, $lb/(ft \cdot sec)$

Equations (1) and (2) are used for liquid, vapor, and two-phase flow regimes. Since the piping is subdivided into small lengths, changes in velocity and physical properties across each segment are assumed to be negligible. At each step in the calculation, a check is made to determine if the fluid velocity has reached or exceeded the computed critical (sonic) velocity for the fluid. If the critical velocity has been exceeded, the velocity is constrained to the critical velocity and the maximum mass flow rate in the piping has been set.

If the fluid in the piping is in two-phase flow, the Lockhart and Martinelli [1949] modification to Equation (1) is used. The Lockhart and Martinelli equation for head loss is shown below:

$$h_{TP} = \Phi^2 \cdot \left(\frac{4 \cdot f \cdot L \cdot U_{ls}^2}{2 \cdot g_c \cdot D_e} \right) \tag{3}$$

where: h_{TP} = head loss for two-phase flow, ft of fluid
Φ = empirical parameter correlating single- and two-phase flow, dimensionless
U_{ls} = superficial liquid velocity (velocity of liquid if liquid filled the pipe), ft/sec

This equation is valid over short distances where the flowing velocity does not change appreciably.

Validation

Validation of fluid flow models is difficult since little data are available for comparison. Fletcher [1983] presented a set of data for flashing CFC-11 flowing through orifices and piping. Figures E-1 through E-4 compare calculations made using the Fluid Release Model with the data presented by Fletcher. Figure E-1 compares fluid fluxes for orifice type releases. These releases had length-to-diameter (L/D) ratios less than 0.88. Figure E-2 compares computed and experimental release fluxes for an L/D ratio of 120 at several levels of storage pressure. Figure E-3 compares similar releases for an L/D of 37.5. Figure E-4 shows predicted and experimental release fluxes at a given pressure for L/D ratios from 1 to 200.

Figures E-5 and E-6 compare computed and experimental gas discharge rates for the complete breach of two pipes. One pipe had an internal diameter of 6.2 inches (0.157 m); the other had a diameter of 12 inches (0.305 m). These pipes were initially pressurized to 1,000 psia with air and then explosively ruptured. The experimental values were reported in a research paper for Alberta Environment, authored by Wilson [1981].

Aerosols and Liquid Droplet Evaporation

Liquids stored at temperatures above their atmospheric pressure boiling point (superheated liquids) will give off vapor when released from storage. If the temperature of storage is sufficiently above the normal boiling point, the energy of the released vapor will break the liquid stream into small droplets. If these droplets are small enough, they will not settle, but remain in the vapor stream as aerosol droplets. The presence of aerosol droplets in the vapor stream changes its apparent density and provides an additional source of vapor. Droplets large enough to fall to the ground will lose mass due to evaporation during their fall.

The prediction of aerosol formation and amount of aerosol formed is based on the theoretical work performed for the Center for Chemical Process Safety (CCPS) by CREARE. CREARE's work has been extended and corrected by Quest. The extension to the model computes the non-aerosol drop evaporation. In Figure E-7, the four experimental data sets available for comparison (chlorine (Cl_2), methylamine (MMA), CFC-11, and cyclohexane) are compared to the values computed by the CANARY Aerosol Model.

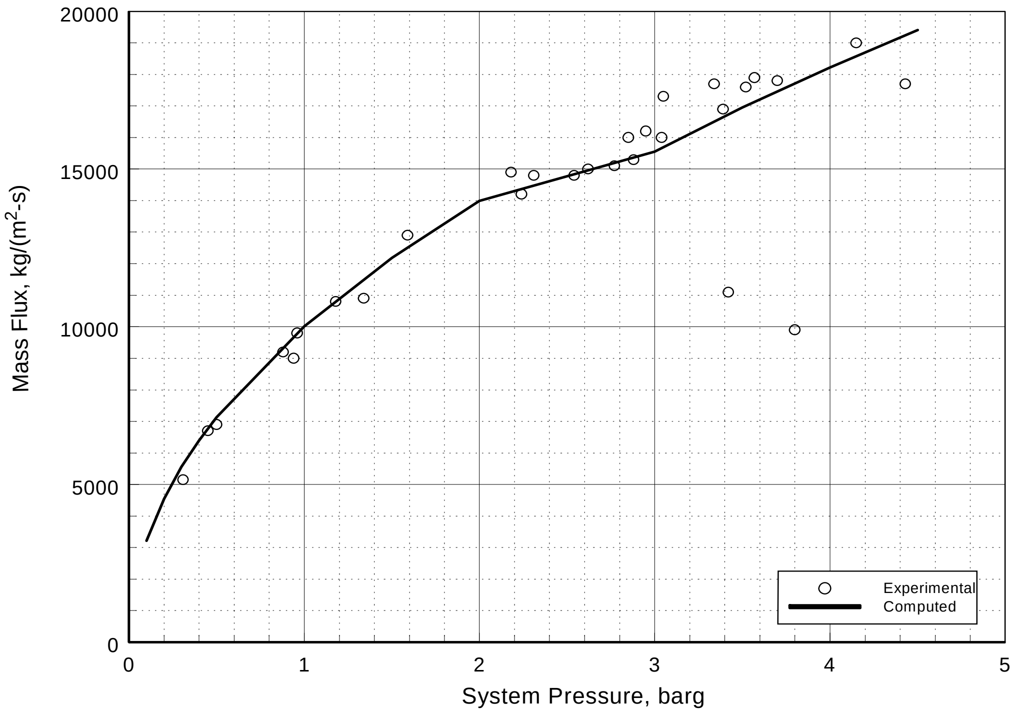

Figure E-1
Comparison of CFC-11 Orifice Releases as a Function of System Pressure

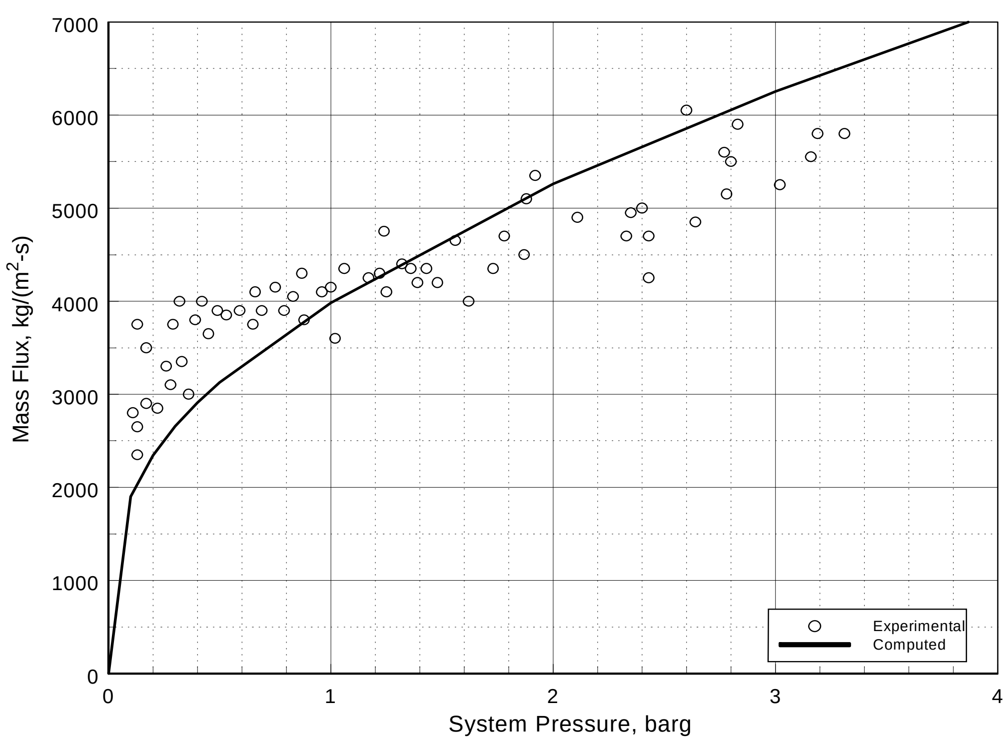

Figure E-2
CFC-11 Release Rate Comparison with L/D of 120

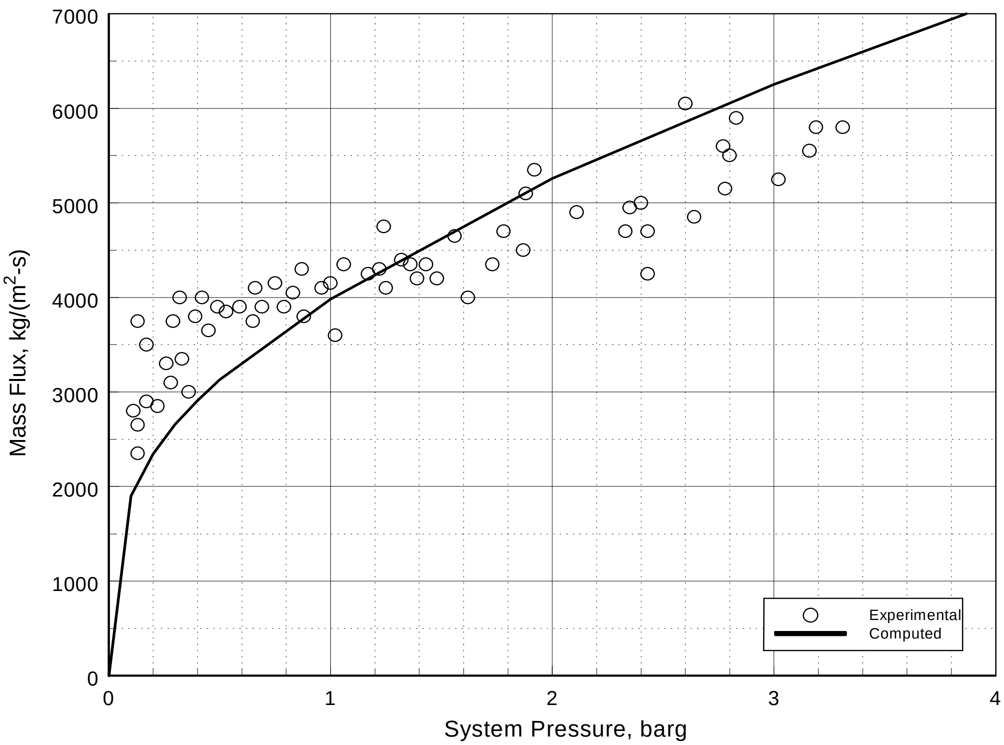

Figure E-3
CFC-11 Release Rate Comparison with L/D of 37.5

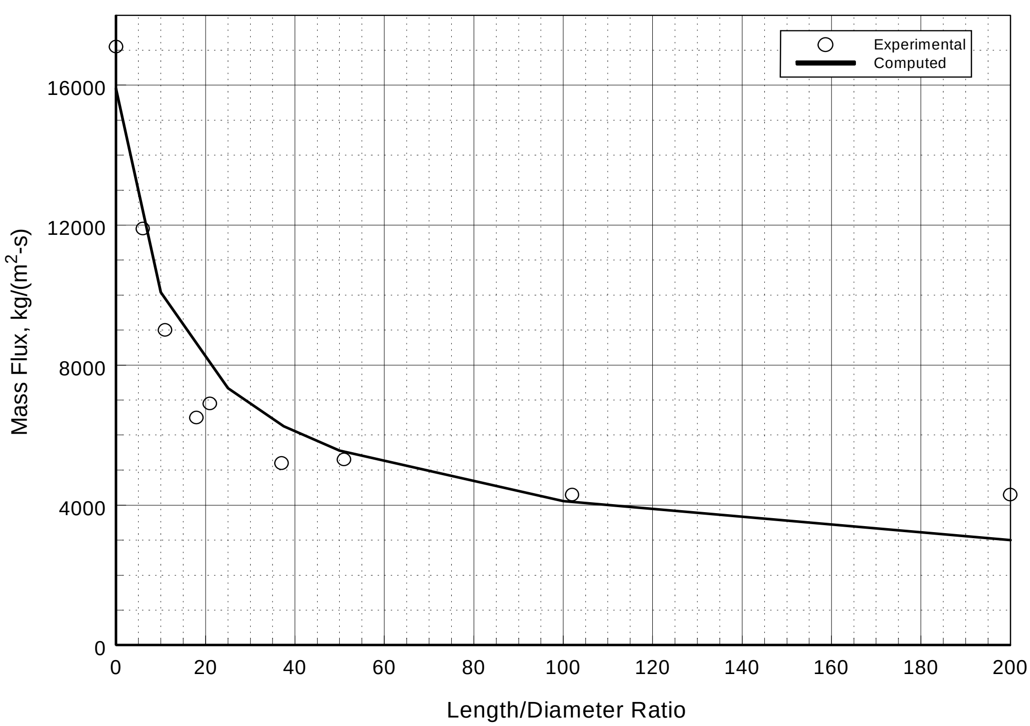

Figure E-4
CFC-11 Release Rate Comparison at Varying L/D Ratios

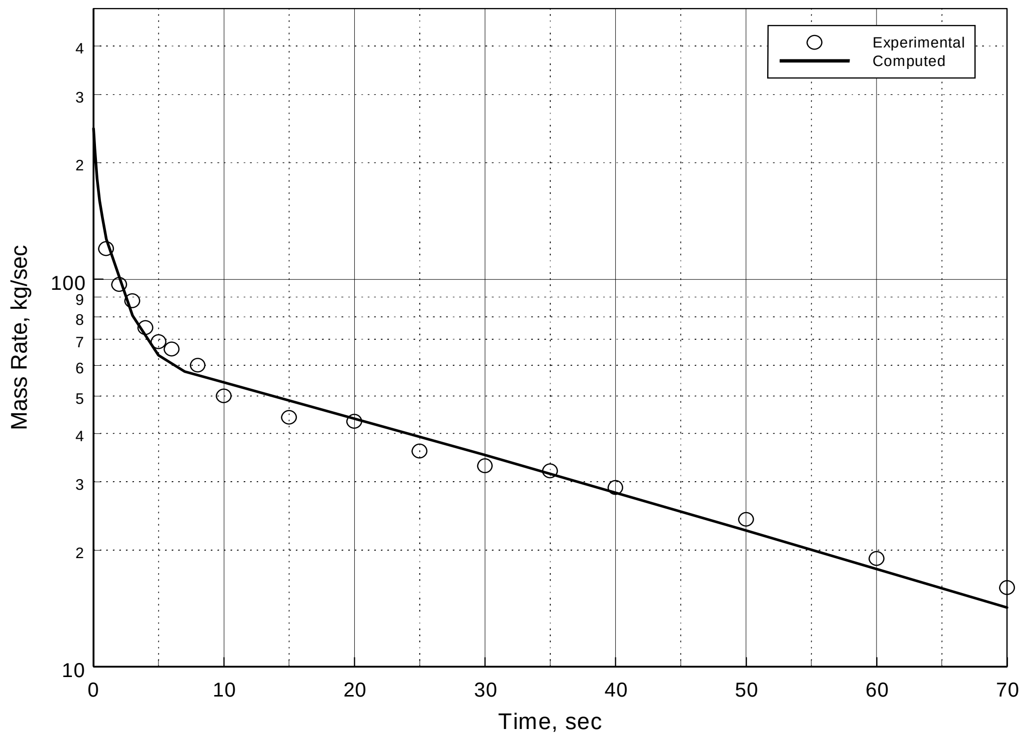

Figure E-5
Air Discharge Rates for 0.157 m Diameter Piping

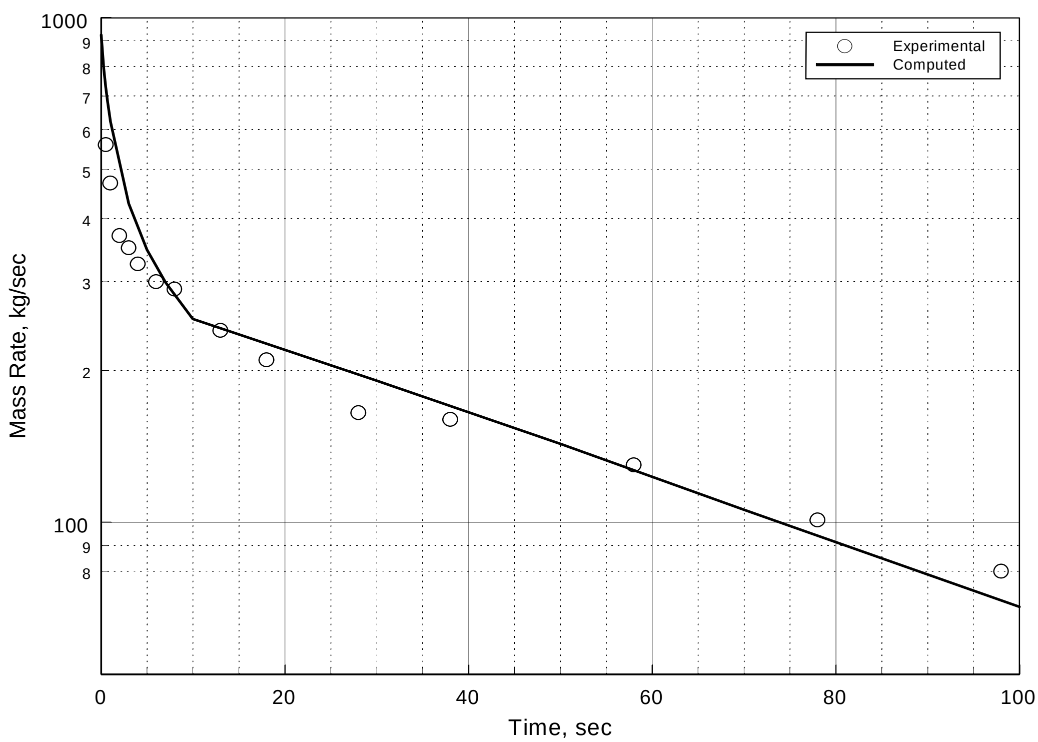

Figure E-6
Air Discharge Rates for 0.305 m Diameter Piping

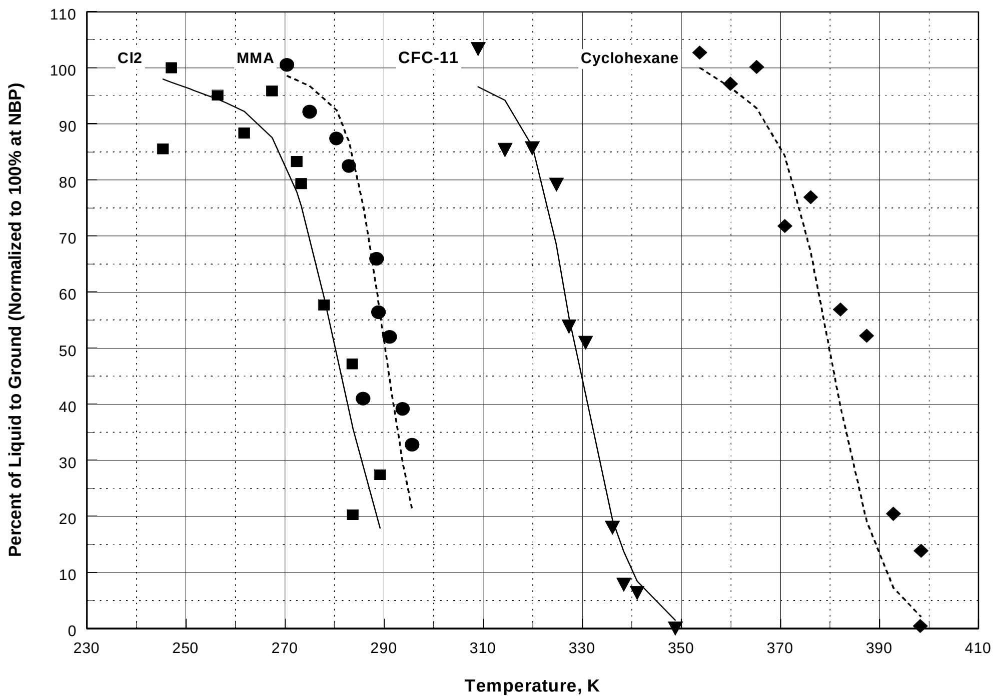

Figure E-7
Aerosol Formation as a Function of Storage Temperature

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Momentum Jet Dispersion Model

Purpose

The purpose of this model is to predict the dispersion of a jet release into ambient air. It is used to predict the downwind travel of a flammable or toxic gas or aerosol momentum jet release.

Required Data

(a) Composition and properties of the released material
(b) Temperature of released material
(c) Release rate of material
(d) Vertical release angle relative to wind direction
(e) Height of release
(f) Release area
(g) Ambient wind speed
(h) Ambient Pasquill-Gifford stability class
(i) Ambient temperature
(j) Relative humidity
(k) Surface roughness scale

Methodology

Step 1: An assumption is made that flow perpendicular to the main flow in the plume is negligible, that the velocity and concentration profiles in the jet are similar at all sections of the jet, that molecular transport in the jet is negligible, and that longitudinal turbulent transport is negligible when compared to longitudinal convective transport. The coordinate system is then defined in s and r, where s is the path length of the plume and r is the radial distance from the plume centerline. The angle between the plume axis and horizontal is referred to as θ. Relationships between the downwind coordinate, x, vertical coordinate, y, and plume axis are given simply by:

$$\frac{dx}{ds} = \cos(\theta) \tag{1}$$

and

$$\frac{dy}{ds} = \sin(\theta) \tag{2}$$

Step 2: Velocity, concentration, and density profiles are assumed to be cylindrically symmetric about the plume axis and are assumed to be Gaussian in shape. The three profiles are taken as:

$$u(s,r,\theta) = U_a \cdot \cos(\theta) + u^*(s) \cdot e^{\frac{-r^2}{b^2(s)}} \tag{3}$$

where: u = plume velocity, m/s
U_a = ambient wind speed, m/s
u^* = plume velocity relative to the wind in the downwind direction at the plume axis, m/s
$b(s)$ = characteristic width of the plume at distance s from the release, m

$$\rho(s,r,\theta) = \rho_a + \rho^*(s) \cdot e^{\frac{-r^2}{\lambda^2 \cdot b^2(s)}} \tag{4}$$

where: ρ = plume density, kg/m^3
ρ_a = density of ambient air, kg/m^3
$\rho^*(s)$ = density difference between plume axis and ambient air, kg/m^3
λ^2 = turbulent Schmidt number, 1.35

$$c(s,r,\theta) = c^*(s) \cdot e^{\frac{-r^2}{\lambda^2 \cdot b^2(s)}} \tag{5}$$

where: c = pollutant concentration in the plume, kg/m^3
$c^*(s)$ = pollutant concentration at plume centerline, kg/m^3

Step 3: The equation for air entrainment into the plume and the conservation equations can then be solved. The equation for air entrainment is:

$$\frac{d}{ds}\left(\int_0^{b\sqrt{2}} \rho \cdot u \cdot 2 \cdot \pi \cdot dr\right) \tag{6}$$
$$= 2 \cdot \pi \cdot b \cdot \rho_a \cdot \left\{\alpha_1 \cdot |u^*(s)| + \alpha_2 \cdot U_a \cdot |\sin(\theta)| \cos(\theta) + \alpha_3 \cdot u'\right\}$$

where: α_1 = entrainment coefficient for a free jet, 0.057
α_2 = entrainment coefficient for a line thermal, 0.5
α_3 = entrainment coefficient due to turbulence, 1.0
u' = turbulent entrainment velocity (root mean square of the wind velocity fluctuation is used for this number), m/s

Step 4: The equations of conservation of mass, momentum, and energy are given as:

$$\frac{d}{ds}\left(\int_0^{b\sqrt{2}} c \cdot u \cdot 2 \cdot \pi \cdot dr\right) = 0 \tag{7}$$

$$\frac{d}{ds}\left(\int_0^{b\sqrt{2}} \left(\rho \cdot u^2 \cdot \cos(\theta) \cdot 2 \cdot \pi \cdot dr\right)\right) \tag{8}$$
$$= 2 \cdot \pi \cdot b \cdot \rho_a \cdot \left\{\alpha_1 \cdot \left|u^*(s)\right| + \alpha_2 \cdot U_a \cdot \left|\sin(\theta)\right| \cdot \cos(\theta) + \alpha_3 \cdot u'\right\}$$
$$+ C_d \cdot \pi \cdot b \cdot \rho_a \cdot U_a^2 \left|\sin(\theta)\right|$$

$$\frac{d}{ds}\left(\int_0^{b\sqrt{2}} \rho \cdot u^2 \cdot \cos(\theta) \cdot 2 \cdot \pi \cdot dr\right) \tag{9}$$
$$= \int_0^{b\sqrt{2}} g \cdot (\rho_a - \rho)\, \pi \cdot r \cdot dr \pm C_d \cdot \pi \cdot b \cdot \rho_a \cdot U_a^2 \cdot \sin(\theta) \cdot \cos(\theta)$$

$$\frac{d}{ds}\left(\int_0^{b\sqrt{2}} \rho \cdot u \left(\frac{1}{\rho} - \frac{1}{\rho_{a0}}\right) \cdot 2 \cdot \pi \cdot r \cdot dr\right) \tag{10}$$
$$= \rho_a \cdot 2 \cdot \pi \cdot b \left(\frac{1}{\rho_a} - \frac{1}{\rho_{a0}}\right) \cdot \left\{\alpha_1 \cdot |u^*(s)| + \alpha_2 \cdot U_a \ \sin(\theta)| \cdot \cos(\theta) + \alpha_3 \cdot \acute{u}\right\}$$

The subscript 0 refers to conditions at the point of release. These equations are integrated along the path of the plume to yield the concentration profiles as a function of elevation and distance downwind of the release.

Step 5: After the steady-state equations are solved, an along-wind dispersion correction is applied to account for short-duration releases. This is accomplished using the method outlined by Palazzi, et al. [1982].

Step 6: If the plume reaches the ground, it is coupled to the Heavy Gas Dispersion Model (described in Section G) and the dispersion calculations continue.

Validation

The Momentum Jet Dispersion Model used in CANARY was validated by comparing results obtained from the model with experimental data from field tests. Data used for this comparison and the conditions used in the model were taken from an American Petroleum Institute (API) study [Hanna, Strimaitis, and Chang, 1991]. For this model, comparisons were made with the Desert Tortoise, Goldfish, and Prairie Grass series of dispersion tests. Results of these comparisons are shown in Figure F-1.

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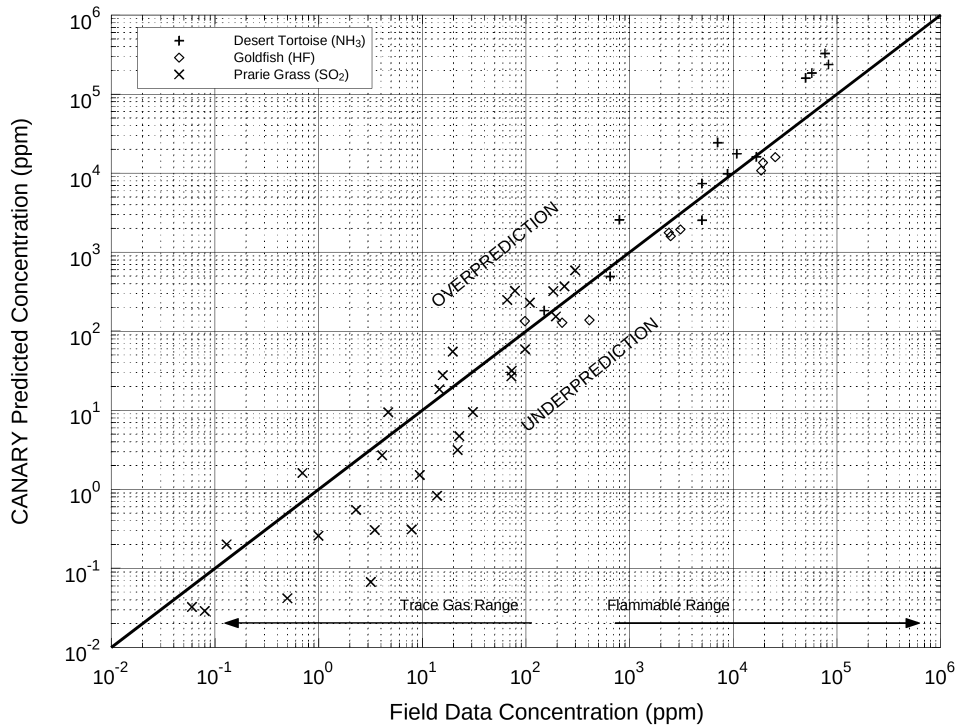

Figure F-1

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Heavy Gas Dispersion Model

Purpose

The purpose of this model is to predict the dispersion and gravity flow of a heavy gas released into the air from liquid pools or instantaneous gas releases. It is used to predict the downwind travel of a flammable or toxic vapor cloud.

Required Data

(a) Composition and properties of the released material
(b) Temperature of released material
(c) Vapor generation rate
(d) Vapor source area
(e) Vapor source duration
(f) Ambient wind speed
(g) Ambient Pasquill-Gifford atmospheric stability class
(h) Ambient temperature
(i) Relative humidity
(j) Surface roughness scale

Methodology

Step 1: For a steady-state plume, released from a stationary source, the Heavy Gas Dispersion Model solves the following equations:

$$\frac{d}{dx}\left(\rho \cdot U \cdot B \cdot h \cdot m\right) = \rho_s \cdot W_s \cdot B_s \tag{1}$$

$$\frac{d}{dx}\left(\rho \cdot U \cdot B \cdot h\right) = \rho_a \cdot \left(V_e \cdot h + W_e \cdot B\right) + \rho_s \cdot W_s \cdot B_s \tag{2}$$

$$\frac{d}{dx}\left(\rho \cdot U \cdot B \cdot h \cdot C_p \cdot T\right) = \rho_a \cdot \left(V_e \cdot h + W_e \cdot B\right) \cdot C_{pa} \cdot T_a + \rho_s \cdot W_s \cdot B_s \cdot C_{ps} \cdot T_s + f_t \tag{3}$$

$$\begin{aligned}\frac{d}{dx}\left(\rho \cdot U \cdot B \cdot h \cdot U\right) \\ = -0.5 \cdot \alpha_g \cdot g \cdot \frac{d}{dx}\left[\left(\rho - \rho_a\right) \cdot B \cdot h^2\right] + \rho_a \cdot \left(V_e \cdot h + W_e \cdot B\right) \cdot U_a + f_u\end{aligned} \tag{4}$$

$$\frac{d}{dx}\left(\rho \cdot U \cdot B \cdot h \cdot V_g\right) = g \cdot \left(\rho - \rho_a\right) \cdot h^2 + f_{vg} \tag{5}$$

$$U \cdot \frac{dZ_c}{dx} = -V_g \cdot \frac{Z_c}{B} \tag{6}$$

$$U \cdot \frac{dB}{dx} = \frac{\rho_a}{\rho} \cdot V_e + V_g \tag{7}$$

$$\rho \cdot T = \frac{\rho_a \cdot T_a \cdot M_s}{\left[M_s + \left(M_a - M_s\right) \cdot m\right]} \tag{8}$$

where:
- x = downwind distance, m
- ρ = density, kg/m^3
- U = velocity in the direction of the wind, m/s
- B = cloud width parameter, m
- h = cloud height parameter, m
- m = mass fraction of source gas
- T = temperature, K
- C_p = specific heat, J/(kg$\cdot$K)
- f_t = ground heat flux, J/(m$\cdot$s)
- f_u = downwind friction term, kg/s^2
- f_v = crosswind friction term, kg/s^2
- V_e = horizontal entrainment rate, m/s
- V_g = horizontal crosswind gravity flow velocity, m/s
- W_e = vertical entrainment rate, m/s
- W_s = vertical source gas injection velocity, m/s
- M = molecular weight, kg/kmole
- s = refers to source properties
- a = refers to ambient properties

The first six equations are crosswind-averaged conservation equations. Equation (7) is the width equation, and Equation (8) is the equation of state.

Step 2: All of the gas cloud properties are crosswind averaged. The three-dimensional concentration distribution is calculated from the average mass concentration by assuming the following concentration profile:

$$C\left(x, y, z\right) = C\left(x\right) \cdot C_1\left(y\right) \cdot C_2\left(z\right) \tag{9}$$

$$C\left(x\right) = \frac{M_a \cdot m\left(x\right)}{M_s + \left(M_a - M_s\right) \cdot m\left(x\right)} \tag{10}$$

$$C_1\left(y\right) = \frac{1}{4 \cdot b} \cdot \left\{ erf\left(\frac{y+b}{2 \cdot \beta}\right) - erf\left(\frac{y-b}{2 \cdot \beta}\right) \right\} \tag{11}$$

$$B^2 = b^2 + 3 \cdot \beta^2 \tag{12}$$

$$C_2(z) = \left(\frac{6}{\pi}\right)^{1/2} \cdot \frac{1}{h} \cdot \exp\left(\frac{-3 \cdot z^2}{2 \cdot h^2}\right) \tag{13}$$

where: $C(x, y, z)$ = concentration in plume at $x, y, z,$ kg/m^3
y = crosswind coordinate, m
z = vertical coordinate, m
b, B, β = half-width parameters, m

Step 3: As there are now two parameters used to define $C_1(y)$, the following equation is needed to calculate b:

$$U \cdot \left(\frac{db}{dx}\right) = V_g \cdot \frac{b}{B} \tag{14}$$

Step 4: The vertical entrainment rate is defined to be:

$$W_e = \frac{\sqrt{3} \cdot a \cdot k \cdot U_* \cdot \delta\left(\frac{h}{H}\right)}{\Phi_h\left(\frac{h}{L}\right)} \tag{15}$$

where: a = constant, 1.5
k = constant, 0.41
U_* = friction velocity, m/s
L = Monin-Obukhov length derived from the atmospheric stability class

Step 5: The profile function δ is used to account for the height of the mixing layer, H, and to restrict the growth of the cloud height to that of the mixing layer. H is a function of stability class and is defined as:

$$\delta\left(\frac{h}{H}\right) = 1 - \frac{h}{H} \tag{16}$$

The Monin-Obukhov function, Φ_h, is defined by:

$$\Phi_h\left(\frac{h}{L}\right) = \begin{cases} 1 + 5 \cdot \frac{h}{L} & L \geq 0 \text{ (stable)} \\ \left[1 - 16 \cdot \frac{h}{L}\right]^{-1/2} & L < 0 \text{ (unstable)} \end{cases} \tag{17}$$

Step 6: After the steady-state equations are solved, an along-wind dispersion correction is applied to account for short-duration releases. This is accomplished using the method outlined by Palazzi, et al. [1982].

Validation

The Heavy Gas Dispersion Model used in CANARY was validated by comparing results obtained from the model with experimental data from field tests. Data used for this comparison and the conditions used in the model were taken from an American Petroleum Institute (API) study [Hanna, Strimaitis, and Chang, 1991]. For this model, comparisons were made with the Burro, Maplin Sands, and Coyote series of dispersion tests. Results of these comparisons are shown in Figure G-1.

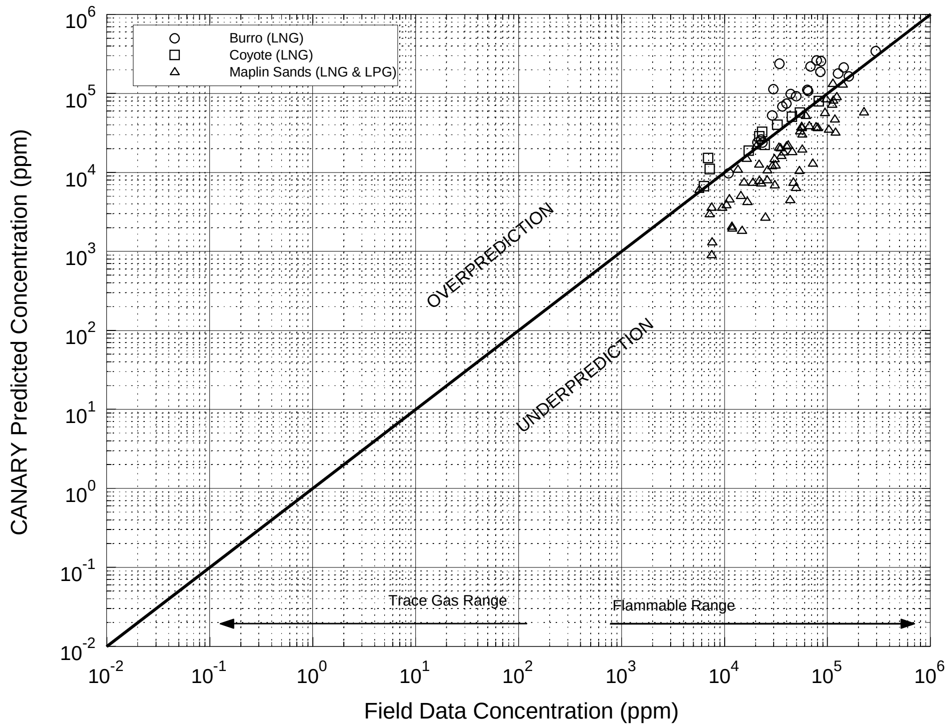

Figure G-1

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Vapor Cloud Explosion Model

Purpose

The purpose of this model is to predict the overpressure field that would be produced by the explosion of a partially confined and/or obstructed fuel-air cloud, based on the Baker-Strehlow methodology. Specifically, the model predicts the magnitude of the peak side-on overpressure and specific impulse as a function of distance from the source of the explosion.

Required Data

(a) Composition of the fuel (flammable fluid) involved in the explosion
(b) Total mass of fuel in the flammable cloud at the time of ignition or the volume of the partially-confined/obstructed area
(c) Fuel reactivity (high, medium, or low)
(d) Obstacle density (high, medium, or low)
(e) Flame expansion (1-D, 2-D, 2½-D, or 3-D)
(f) Reflection factor

Methodology

Step 1: The combustion energy of the cloud is estimated by multiplying its mass by the heat of combustion. If the volume of the flammable cloud is input, the mass is estimated by assuming that a stoichiometric mixture of gas and air exists within that volume.

Step 2: The combustion energy is multiplied by the reflection factor to account for blast reflection from the ground or surrounding objects.

Step 3: Flame speed is determined from the fuel reactivity, obstacle density, and flame expansion parameters, as presented in Baker, et al. [1994, 1998].

Fuel reactivity and obstacle density each have low, medium, and high choices. The flame expansion parameter allows choices of 1-D, 2-D, 2.5-D, and 3-D. The choices for these three parameters create a matrix of 36 possibilities, thus allowing locations that have differing levels of congestion or confinement to produce different overpressures. Each matrix possibility corresponds to a flame speed, and thus a peak (source) overpressure. The meanings of the three parameters and their options are:

Fuel Reactivity (High, Medium, or Low). The fuels considered to have high reactivity are acetylene, ethylene oxide, propylene oxide, and hydrogen. Low reactivity fuels are (pure) methane and carbon monoxide. All other fuels are medium reactivity. If fuels from different reactivity categories are mixed, the model recommends using the higher category unless the amount of higher reactivity fuel is less than 2% of the mixture.

Obstacle Density (High, Medium, or Low). High obstacle density is encountered when objects in the flame's path are closely spaced. This is defined as multiple layers of obstruction resulting in at least a 40% blockage ratio (i.e., 40% of the volume is occupied by obstacles). Low density areas are defined as having a blockage ratio of less than 10%. All other blockage ratios fall into the medium category.

Flame Expansion (1-D, 2-D, 2.5-D, or 3-D). The expansion of the flame front must be characterized with one of these four descriptors. 1-D expansion is likened to an explosion in a pipe or hallway. 2-D expansion can be described as what occurs between flat, parallel surfaces. An unconfined (hemispherical expansion) case is described as 3-D. The additional descriptor of 2.5-D is used for situations that begin as 2-D and quickly transition to 3-D.

Step 4: Based on the calculated flame speed, appropriate blast curves are selected from the figures in Baker, et al., 1994. For flame speeds not shown on the graph, appropriate curves are prepared by interpolation between existing curves.

Step 5: The Sachs scaled distance, $\bar{R}$, is calculated for several distances using the equation:

$$\bar{R} = \frac{R}{\left(\frac{E}{P_0}\right)^{1/3}}$$

where: R = distance from the center of the explosion
E = total energy calculated in step 2, above
P_0 = atmospheric pressure

Step 6: The peak side-on overpressure and specific impulse at each scaled distance are determined from the blast curves in Baker, et al., 1994.

References

Baker, Q. A., M. J. Tang, E. Scheier, and G. J. Silva, "Vapor Cloud Explosion Analysis." *28th Loss Prevention Symposium, AIChE,* 1994.

Baker, Q. A., C. M. Doolittle, G. A. Fitzgerald, and M. J. Tang, "Recent Developments in the Baker-Strehlow VCE Analysis Methodology." *Process Safety Progress*, 1998: p. 297.

APPENDIX C
Base Parameters for Consequence Modeling

Description	Value	Units
Atmospheric Conditions		
Wind speed for dispersion	4.47 [2]	mph [m/s]
Wind speed for fire radiation	12 [5.35]	mph [m/s]
Wind speed measurement height	32.8 [10]	ft [m]
Air temperature	64	F
Relative humidity	66	%
Atmospheric stability (dispersion model only)	F	Pasquill
Spill Surface Conditions		
Surface roughness on land	0.04	m
Surface roughness on water	0.001	m
LNG Parameters		
Evaporation rate on water (FERC Model)	0.1669	kg/m^2-s
Burning rate on water (FERC Model)	0.282	kg/m^2-s
Density of LNG (FERC Model)	422.5	kg/m^3
Surface flux for fire radiation (FERC Model)	265	kW/m^2
LNG Composition		
Nitrogen	0.10	mole %
Methane	86.80	mole %
Ethane	8.10	mole %
Propane	3.40	mole %
Iso-butane	1.60	mole %